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## A THEORY FOR THE CONCENTRATION AND DISTRIBUTION OF COPPER IN THE EARTH'S CRUST.


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ABSTRACT.

Copper occurs in traces, if not in determinable amounts, apparently, throughout the entire crust of the earth; but commercial deposits, although found in every type of rock, occur only where the crust has been fractured, fissured, or sheared. As the earth cooled to temperatures permitting chemical union of the atoms, the interaction of physical and chemical forces, notably gravity and the combination of the elements in the order of the heats of formation of their compounds, depressed the major parts of copper, sulphur, and other of the less chemically active heavy metals and their associated anions to a zone below the silicates where they remained until released through fractures in the solid crust.


THE reserves of copper in the known ore-bodies of the world are estimated at about 100,000,000 metric tons.[1] The percentage of copper in these ores varies from about one-half of one per cent to more than 50 per cent. In addition to these concentrations in commercial ore-bodies copper is also minutely diffused throughout the entire crust of the earth. Geochemists estimate that the outer crust contains an average of 0.01 per cent copper.[2] If that be true the first mile of depth contains two hundred trillion tons of the metal, or two million times as much as is known in ore-bodies. This enormous tonnage is scattered through practically all the materials of the earth's crust, organic as well as inorganic. It is disseminated in igneous rocks both acid and basic, especially in the latter up to several tenths of one per cent. It is present as

[1] Croston, John J.: Trends in copper production, reserves and costs. A. I. M. E. Trans., 126: 327, 1937.

[2] Clarke, F. W., and Washington, H. S.: The composition of the earth's crust. U. S. Geol. Surv. Prof. Pap. 127, 1924.

traces in sea water and in practically all surface rocks and soils. It has been determined quantitatively in a great variety of vegetables, fruits, and seeds, which have been found to contain from one to 17 milligrams per kilogram. A certain African bird, the plantain eater (Tuoracoa), has in the brilliant red pigment of its wing feathers seven per cent of copper. Human blood serum carries from one to two milligrams of copper per liter, and it is believed by some physiologists to be essential to human life.[3]

To gain a rational conception of how this metal could have been so widely diffused through the crust of the earth and also so highly concentrated in a few localities it is necessary to revert to that period in the earth's development when—as is now generally accepted—it was hot and fluid like the sun. Whether we accept the theory that the planets are accumulations of nebulous matter left in rings, or shells, by a shrinking sun, or that they were pulled away from the surface of the sun by the attraction of a passing siderial wanderer,[4] it seems probable that when the earth assumed spheroidal form, the constituents were in a dissociated atomic or subatomic state and in violent agitation owing to the prevailing high temperature. It is also generally believed that the elements during this stage—if they were uniformly distributed at the beginning—would tend by gravity to separate into zones, or shells; the heavier atoms moving toward the center and the lighter ones away from it.

Clarke and Washington estimated that 99.968 per cent of a ten-mile crust, including the hydrosphere and the atmosphere, consists of only 26 of the 92 elements; that five of these which are gases when in the free state make up 50.888 per cent of the total, and that only about five per cent of the total consists of metals having atomic weights greater than 40.[5]

Astronomers state that the temperature of the surface of the sun is 6000 degrees Centigrade; that it has an outer gaseous envelope, the chromosphere, 5000 miles deep, below which is the

[3] White, C. H.: Organisms as guides to copper ore. Min. Mag., London, January, 1929.

[4] Jeans, Sir James: The Universe Around Us, p. 223, 1929.

[5] *Op. cit.*, p. 34.

more luminous photosphere.[6] By means of the spectroscope the following elements have been detected in the chromosphere, hydrogen, helium, carbon, sodium, magnesium, aluminum, silicon, calcium, scandium, titanium, vanadium, chromium, manganese, iron, zinc, strontium, yttrium, zirconium, barium, lanthanum, cerium, neodymium, ytterbium, lead, and europium. It is also revealed that most of the metallic vapors lie close to the photosphere. Twenty other elements, copper among them, have been detected below the chromosphere. Rising out of the surface of the sun are prominences of two kinds, quiescent and eruptive. The former rise to heights as great as 20,000 miles, linger for days in one spot, and show spectra of hydrogen and helium; the eruptive ones contain metals and may rise as high as 350,000 miles at speeds of 100 to 250 miles per second.

It appears, therefore, assuming a like condition for the newborn earth, that although its temperature was too high for chemical combination of the elements to take place, they arranged themselves roughly in spherical shells, or zones, according to their weights, and when the sphere was cool enough on the outside for atoms to combine to form gaseous molecules, the release of heat of formation probably upset the equilibrium and produced turbulences similar to those often observed on the surface of the sun. Possibly at such times the small percentages of the heavy metals at present diffused in the crust were thrown up to be caught and held in chemical union by the lighter anions.

Evidently it would be quite impossible to trace an atom of copper or of any other element in its affiliations and migrations through the several stages from the atomic through the molecular, first as gas and, with further cooling, to liquid and then to solid; but with the information available respecting the specific properties of the elements and of their compounds, and of the forces of nature incident under varying conditions, the probable trend of events as the planet cooled down may be sketched in a general way.

Apparently the two most important natural laws effective at this early stage were the law of gravitation, and Van't Hoff's law

[6] Sampson, R. A.: The Sun. Encyclopedia Britannica, 11th Edit.

of mobile equilibrium which gives an indication of the order in which combinations would take place in the cooling earth. Van't Hoff's law states that in a cooling system combinations take place that give out heat.[7] For example, if copper in contact with oxygen and nitrogen is cooled from a high temperature, the oxygen combines with the copper but the nitrogen does not. The union of copper and oxygen is an exothermic reaction; the heat of formation of CuO is 146 kilojoules, while that of $CuN_3$ is —238 kj., an endothermic reaction.

By implication a corollary to Van't Hoff's law may be formulated as follows: that in a cooling system those combinations take place *first* that give out the *greatest amount* of heat. This is verified in chemical and metallurgical practice; for example, if iron and copper are cooled down from a high temperature in the presence of a limited amount of sulphur, the iron appropriates the sulphur until it is satisfied, leaving only the residue of sulphur to be seized upon by the copper. The heats of formation of their monosulphides are respectively 95.5 kj. and 48.6 kj. Oxygen which has a much stronger affinity for most metals than sulphur also shows a preference for iron over copper and in almost the same ratio (268 kj. to 146 kj.).

If the elements in the cooling earth united in the order of the heats of formation of their compounds, a comparison of the heats of formation or of potentials in the electromotive series, will indicate the trend of events at this early period in the earth's history. Table 1 [8] shows, as far as data are available, the order in which the oxides of the metals would form in a falling temperature.

The rare heavy metals: thallium, lanthanum, neodymium, uranium, cerium, and praseodymium, form highly exothermic compounds, and if they had not already fallen below the zone of the anions before the heat was reduced to the combining temperature, they would be among the first to combine with the anions and take their places in depth as compounds. The more common heavy metals are less exothermic than the light ones and would

[7] Findlay, Alexander: The Phase Rule, p. 46, 1923.

[8] International Critical Tables, 5: 176–207, 1929.

take their places in zones below the light and highly exothermic metals and anions.

TABLE 1.

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| $ThO_2$ | 692 | $UO_2$ | 537 | ZnO | 353 | $H_2O$ | 242 | $RuO_2$ | 110 |
| $La_2O_3$ | 637 | $CeO_2$ | 491 | $Rb_2O$ | 347 | CoO | 241 | $OsO_4$ | 98 |
| CaO | 635 | $PrO_2$ | 450 | $Cs_2O$ | 344 | $Sb_2O_5$ | 231 | HgO | 91 |
| MgO | 610 | $TiO_2$ | 447 | $SnO_2$ | 292 | PbO | 220 | PdO | 90 |
| $Nd_2O_3$ | 607 | $V_2O_5$ | 437 | $Fe_3O_4$ | 279 | $As_2O_3$ | 218 | $In_2O_3$ | 33 |
| $Li_2O$ | 593 | $SiO_2$ | 421 | MoO | 273 | $Bi_2O_3$ | 189 | $Ag_2O$ | 29 |
| BeO | 591 | $Na_2O$ | 415 | CdO | 273 | $CrO_3$ | 189 | $IrO_2$ | 10 |
| $SrO_2$ | 589 | MnO | 380 | $WO_2$ | 264 | $Tl_2O$ | 176 | $Au_2O_3$ | −54 |
| BaO | 557 | $ZrO_2$ | 374 | $Ta_2O_5$ | 251 | $Cu_2O$ | 167 | Pt | No oxide. |
| $Al_2O_3$ | 556 | $K_2O$ | 361 | NiO | 242 | $Sa_2O_3$ | 154 | | |

In Table 1, the numbers are the heats of formation in kilojoules where only one atom of oxygen is involved. With polyvalent elements requiring more than one atom of oxygen in the formula of its oxide the number in each case is not the heat of formation but the fraction obtained by dividing the heat of formation by the number of oxygen atoms involved; that is, the order in the table represents the order in which oxygen would combine with the metals to yield the greatest amount of heat per unit of oxygen. Fractions are omitted.

Tables 1 and 2 are compiled from International Critical Tables, Vol. 5: 176–207.

Tables 1 and 2 show that, with the exception of the metals thallium, lanthanum, neodymium, uranium, cerium, and praseodymium, the lighter metals and the lighter acid-forming elements on combining give out more heat than do combinations of the heavier elements. For example, lithium and fluorine combining yield 609 kj. while gold and iodine yield only 4 kj. Gravitational zoning while in the atomic stage, therefore, would bring into propinquity near the surface of the sphere the highly exothermic elements whose compounds were formed early in the molecular period which now constitute the major part of the crust. Table 1 shows that there are 35 metals that take precedence over copper in the pursuit of compound-forming associates, while only samarium, ruthenium, osmium, mercury, palladium, indium, silver, iridium, gold, and platinum are less active chemically than copper.

Also in the series of anions, or acid-forming ions, sulphur stands below fluorine, oxygen, chlorine, boron, phosphorus, and titanium; therefore, copper and sulphur would be relegated to near the end of the procession of chemical unions. The procession begins with the highly exothermic compounds which remain in the outer zone. Beneath this zone are the heavier and less

TABLE 2.

| | F. | O. | Cl. | S. | Br. | I. | Se. |
|---|---|---|---|---|---|---|---|
| Li | 609 | 593 | 407 | | 350 | 272 | 399 |
| Sr | 604 | 589 | 446 | 473 | 358 | 285 | 377 |
| Ba | 602 | 557 | 466 | 465 | 377 | 303 | |
| Ca | 599 | 634 | 409 | 475 | 339 | 269 | 370 |
| Na | 570 | 415 | 411 | 376 | 361 | 290 | 291 |
| K | 561 | 361 | 436 | 369 | 393 | 329 | 357 |
| Rb | 557 | 347 | 439 | 367 | 402 | 338 | |
| Mg | 552 | 610 | 320 | 344 | 259 | 181 | |
| Cs | 552 | 344 | 445 | 366 | 407 | 350 | |
| Al | 444 | 556 | 232 | 481 | 176 | 99 | |
| Mn | 431 | 380 | 235 | 198 | 190 | 160 | 114 (?) |
| Zn | 402 | 353 | 208 | 192 | 163 | 104 | 140 |
| Fe | 371 | 268 | 171 | 96 | 163 | 99 | 80 |
| Cd | 361 | 273 | 194 | 142 | 153 | 101 | 90 (?) |
| Co | 361 | 241 | 161 | 83 | 115 | 89 | 48 |
| Ni | 358 | 242 | 156 | 87 | 111 | 87 | 56 |
| Pb | 333 | 219 | 179 | 93 | 138 | 87 | 99 |
| Sn | 327 | 292 | 169 | 100 | 128 | 75 | |
| Sb | 302 | 221 | 127 | 50 | 85 | 61 | |
| Cu | 292 | 146 | 136 | 48 | 103 | 66 | 20 |
| Ag | 203 | 29 | 126 | 21 | 99 | 62 | −4 |
| Bi | | 189 | 126 | | | | |
| As | | 218 | 101 | 40 | 64 | 20 | |
| Hg | | 91 | 111 | 45 | 103 | 46 | 17 |
| Pd | | 90 | 91 | | | | |
| Pt | | | 71 | | 42 | 17 | |
| Ir | | 10 | 43 | | | | |
| Au | | −18 | 43 | | 19 | 4 | |

This table shows the order in which the metals and the anions listed would tend to combine in a falling temperature. For example, although the heat of formation of magnesium fluoride ($MgF_2$) is 1104 kj. and that of lithium fluoride (LiF) is 609 kj., two atoms of fluorine are involved in the molecule $MgF_2$ while only one atom of this anion is united with the monovalent lithium atom; therefore, if the fluorine had a free choice it would unite with lithium in preference to magnesium, or to any other element that stands below it in the series. Fractions are omitted.

exothermic, and still lower, copper and sulphur, followed by the more inert metals with selenium and tellurium. Below this zone probably anions do not exist, only the heavy metals.

Assuming that combinations have taken place as indicated, it is next in order to inquire into the behavior or disposition of the resulting compounds. The compounds, as they form, are endowed, each with its specific properties that determine its behavior under the influence of the forces to which it is then amenable. Its inherent properties determine the temperature and pressure at which it will change from vapor to liquid and from liquid to

solid, and how much it shall weigh per cubic centimeter in each of the three states.

TABLE 3.

PHYSICAL CONSTANTS OF HALIDES, OXIDES AND SULPHIDES OF FOUR REPRESENTATIVE METALS IN THE ELECTROMOTIVE SERIES, AND OF CERTAIN ROCK-FORMING MINERALS.

Data from International Critical Tables, Vol. 1: 106–174.

| | Molecular weight. | Sp. Gr. | Melting point, C. | Boiling point, C. | Heat of formation, kj. |
|---|---|---|---|---|---|
| NaF | 41.99 | 2.79 | 980 | 1700 | 570.4 |
| $FeF_2$ | 93.84 | 4.09 | | | 741 |
| $CuF_2$ | 82.57 | | 908 | 1200 | 585 |
| AgF | 126.88 | 5.85 | 435 | | 203.8 |
| NaCl | 58.45 | 2.16 | 800 | 1413 | 411.64 |
| $FeCl_2$ | 126.75 | 2.7 | | 448 | 342.6 |
| $CuCl_2$ | 134.48 | 3.05 | 498 | 993 | 215.2 |
| AgCl | 143.33 | 5.56 | 455 | 1550 | 126.6 |
| NaBr | 102.91 | 3.2 | 755 | 1390 | 361.3 |
| $FeBr_2$ | 215.67 | 4.63 | | | 326 |
| $CuBr_2$ | 143.48 | 4.72 | 504 | 1345 | 103 |
| AgBr | 187.79 | 6.47 | 434 | | 99.8 |
| NaI | 149.93 | 3.66 | 651 | 1300 | 290.7 |
| $FeI_2$ | 309.70 | | 177 | | 199 |
| CuI | 190.50 | 5.6 | 605 | 1290 | 66 |
| AgI | 234.81 | 5.6 | d. 552 | | 62.5 |
| $Na_2O$ | 61.99 | 2.27 | | | 415 |
| FeO | 71.84 | | 1420 | | 268 |
| CuO | 79.57 | 6.4 | d. 1026 | | 146 |
| $Ag_2O$ | 231.76 | 7.14 | d. 300 | | 29.1 |
| $Na_2S$ | 78.06 | 1.85 | | | 376 |
| FeS | 87.90 | 4.8 | 1193 | | 80 |
| CuS | 95.63 | 4.6 | tr. 103 | | 48.6 |
| $Cu_2S$ | 159.20 | 5.6 | 1100 | | 79.4 |
| $Ag_2S$ | 247.82 | 7.31 | tr. 175 | | 21 |

| | | |
|---|---|---|
| Microcline | 2.55 | 1150 |
| Orthoclase | 2.57 | 1170 |
| Leucite | 2.45 | +1800 |
| Anorthite | 2.75 | 1555 |
| Albite | 2.62 | 1120 |
| Biotite | 2.7 | 1160 |
| Muscovite | 2.76 | 1260 |
| Olivine | 3.30 | 1390 |
| Augite | 3.19 | 1165 |
| Hornblende | 3. | 1080 |
| Diopside | 3.3 | 1395 |
| Quartz | 2.65 | <1470 |
| Magnetite | 5.8 | d. 1538 |
| Hematite | 5.2 | d. 1560 |

Table 3[9] shows the molecular weight, specific gravity, melting point, boiling point, and the heat of formation of the halides, oxides, and sulphides of sodium, iron, copper, and silver—four widely separated representatives of the electromotive series. Appended to the table for comparison are specific gravities and melting points of rock-forming silicates and oxides. The table indicates in a general way that in a series of binary compounds consisting of an anion combined with a series of metals from light to heavy, the specific gravity of the compound increases as the atomic weight of the metal increases, but the melting point and the heat of formation decrease. This table also shows that the halogen salts are volatile at temperatures not much higher than the melting points of the silicates, and that when the silicates become solid the salts are still molten, and, being less dense, would rest upon the surface of the silicates.

The sulphides, oxides, and salts of the heavy metals being denser than the rock-forming silicates would naturally take their places below the silicates while still in liquid form. If by chance these heavy compounds were thrown up by eruptive forces into the silicate zone, while still fluid, the sulphides and other compounds that could not form new exothermic unions in the new environment would, except for traces, return by gravity to their former places in depth. It appears, therefore, that by the time the solid crust began to form, gaseous or liquid shells, or zones, would be well established in the following order: on the outside, hydrogen and helium; next below, an atmosphere of nitrogen, oxygen, and carbon dioxide, in which would be suspended, as vapor, all the water of the hydrosphere; below the atmosphere would be found volatile salts, followed by acid magma many miles deep, highly silicious at the surface, more basic below. As the silica decreases oxides increase, followed by decreasing oxides and increasing sulphides, selenides, and tellurides, and lower still only the heavy metals.

Necessarily these zones, or shells, could not be wholly unmixed. A gradual transition—not a sharp one—would be expected in

[9] International Critical Tables, 1: 106–174, 1926.

passing from one zone to the next, and small amounts of the denser minerals would remain entangled in the less dense magmas. No doubt, in this way traces of copper were left minutely diffused throughout the whole of the silicate and oxide zones, increasing in quantity downward, while the major part was segregated at greater depth in the zone of sulphide concentrate, or ore zone.

After the crust had solidified and the temperature had fallen below the boiling point of water, rain carried away the surface deposits of soluble salts of the alkalies and of other bases into the sea. Erosion removed the highly silicious crust and laid it on the sea floor to be consolidated into Algonkian quartzite. At this stage of the earth's development, according to this theory, there were no copper ore-bodies in the solid crust. All the earth's copper was either (1) minutely diffused in traces throughout the crust, or (2) highly concentrated in a zone at abyssal depth associated with sulphur and other of the less chemically active elements.

This opinion, although in opposition to that generally accepted, that is, that most copper ore-bodies had their origin in discrete bodies of magma injected into the crust, is in accordance with that held by a few advocates that have appeared from time to time in favor of a "deeper than crust origin." Descartes three hundred years ago held the opinion that the metallic minerals in veins come from a "shell of very heavy matter below the stony outer crust."[10] Gregory in 1928 wrote in his *Elements of Economic Geology,* "The source of the ores appears to lie in a zone deeper than that of ordinary igneous rocks." Holmes on the basis of the difference between the atomic weight of ore-lead and rock-lead, which is partly radiogenetic, believes that ore-lead comes from a deeper source than magmatic intrusions in the crust.[10] Wells[11] and Graton[12] hesitate to discard the generally accepted

[10] Holmes, Arthur: Origin of primary lead ores. ECON. GEOL., 32: 764–782, 1937 and 33: 829–865, 1938.

[11] Wells, R. C.: The origin of primary lead ores. ECON. GEOL., 33: 216–217, 1938.

[12] Graton, L. C.: Ores: from magmas, or deeper? A reply to Arthur Holmes. ECON. GEOL., 33: 251–286, 1938.

theory on the evidence offered by Holmes. Kelley[13] in his studies at the Darwin silver-lead deposits in California found evidence for a "deep seated supply of metals and their associated gangue substances following the consolidation of the intrusive and the fracture of the rocks." Spencer[14] says of the ore at Ely (Nevada), "it is obvious that these solutions came from a source outside the immediate mass of the igneous rocks."

If the theory of an abyssal ore-zone is accepted tentatively, it is next in order to indicate a rational mechanism by which the ore could be transferred from this zone to the outer crust and concentrated in commercial bodies within reach of human ingenuity. Preliminary to the formulation of a theory to account for the origin of copper deposits it will be profitable to review the geological settings of the various types of important copper deposits of the world; their position in the earth's crust, their form and size, the rocks in which they are held, and their mineral associates.

Data assembled from reports[15] on 81 mines and districts responsible for most of the world's production of copper are summarized in the following paragraphs.

1. The known copper deposits occur within about one mile of the surface and are associated with faults, fractures, fissures or sheared, crushed or other permeable zones.

2. Copper ores have been deposited in many geologic periods from pre-Cambrian to Late Tertiary, especially following periods of profound crustal deformation.

3. Copper deposits are held in rocks of all types: igneous, sedimentary, and metamorphic. The occurrences of the several types of rocks in the 81 mines and districts are as follows: sedimentary rocks are found in 76 districts, including limestone (in 25),

[13] Kelley, V. C.: Origin of the Darwin silver-lead deposits. Econ. Geol., 32: 987–1008, 1937.

[14] Spencer, A. C.: The geology and ore deposits of Ely, Nevada. U. S. Geol Surv., Prof. Pap. 96: 61, 1917.

[15] The data on copper deposits were compiled from many sources: reports in Economic Geology; the Sixteenth International Geological Congress; publications of the U. S. Geological Survey; U. S. Bureau of Mines; and others. The figures given are only an indication of relative frequency of occurrence. Many reports are incomplete making it impossible to give accurate totals.

sandstone, quartzite, shale, slate (sedimentary), conglomerate, greywacke, dolomite, marl, and arkose. Igneous rocks occur in 73 districts, including granite and granite porphyry in 12, monzonite, quartz monzonite, and quartz monzonite porphyry in 9, andesite in 9, granodiorite in 6, rhyolite and other acidic lavas, breccias, tuffs, and schists in 11, diorite in 8, basic lavas in 4, gabbro and dacite in 3 each, alaskite in two, and dunite in one.

Schists occur in 25, including the following varieties: sericite, chlorite, greenstone, muscovite, and graphite.

4. It is worthy of note that basic dikes or other basic intrusive bodies occur in 57 of the districts, and that in many of them minutely disseminated copper sulphides, apparently syngenetic, have been reported. On the other hand, intrusive stocks, or batholiths of intermediate or more acid rocks are found in only 34 of the districts.

5. Although copper deposits usually include a variety of copper-bearing minerals—carbonates, oxides, silicate, native copper, and others as well as sulphides, it is now pretty well established that the copper deposited by hypogene mineralization came up originally associated with sulphur, and generally also associated with iron, zinc, lead, and other heavy metals; that those ores which contain oxygen are supergene alteration products, and that deposits of native copper like those at Lake Superior and at Corocoro were robbed of their sulphur by the oxidizing agents in the invaded rocks.

6. More than a score of hypogene sulphides and related minerals occur in copper deposits. In the 81 mines and districts under review, chalcopyrite is reported in 74, bornite in 18, chalcocite in 15, tetrahedrite in 10, enargite in 8, tennantite in 4, cubanite and chalmersite in two each, and the following, usually in very small amounts, in one district each: bournonite, luzonite, and covellite.

7. Of the non-copper-bearing sulphides associated with copper ores, the following are reported: pyrite in 63, sphalerite in 34, galena in 19, pyrrhotite in 16, molybdenite in 7, and arsenopyrite in 6.

8. Of the three score or more of metamorphic minerals, other than sulphides that have been found associated with copper ores, quartz is the most prevalent. It is reported as an alteration mineral in 48 districts. Others in the order of frequency of occurrence are chlorite in 30, sericite in 25, calcite in 22, garnet, epidote, and magnetite in 16 each, biotite in 11, hematite in 8, actinolite and tourmaline in 7 each, hornblende and barite in 6 each, cordierite in 5, zoisite, wollastonite, tremolite, diopside, and alunite in 4 each, anthophyllite, prehnite, andalusite, feldspar, fluorite, and siderite in 3 each, hedenbergite, spinel, and rutile in two each, and cummingtonite, scapolite, hypersthene, vesuvianite, graphite, delessite, ilvaite, babingtonite, sillimanite, analcite, laumontite, stilbite, titanite, ankerite, rhodochrosite, dolomite, anhydrite, fuchsite, uvarovite, and gypsum in one each.

TABLE 4.

COMPOSITION OF THE MORE IMPORTANT HYPOGENE SULPHIDES.[16]

| | Cu. | S. | Fe. | As. | Sb. | Pb. | Zn. | Ni. | Mo. |
|---|---|---|---|---|---|---|---|---|---|
| Chalcocite | 79.8 | 20.2 | | | | | | | |
| Bornite | 63.3 | 25.6 | 11.1 | | | | | | |
| Chalcopyrite | 34.5 | 35.0 | 30.5 | | | | | | |
| Cubanite | 20.9 | 42.3 | 36.8 | | | | | | |
| Chalmersite | 23.5 | 35.4 | 41.1 | | | | | | |
| Covellite | 66.4 | 33.6 | | | | | | | |
| Enargite | 48.3 | 32.6 | | 19.1 | | | | | |
| Tennantite | 57.5 | 25.5 | | 17.0 | | | | | |
| Luzonite | 48.3 | 32.6 | | 19.1 | | | | | |
| Tetrahedrite | 52.1 | 23.1 | | | 24.8 | | | | |
| Bournonite | 13.0 | 19.8 | | | 24.7 | 42.5 | | | |
| Pyrite | | 53.4 | 46.6 | | | | | | |
| Pyrrhotite | | 39.6 | 60.4 | | | | | | |
| Arsenopyrite | | 19.7 | 34.3 | 46.0 | | | | | |
| Galena | | 13.4 | | | | 86.6 | | | |
| Sphalerite | | 33.0 | | | | | 67.0 | | |
| Pentlandite | | 36.0 | 42.0 | | | | | 22.0 | |
| Molybdenite | | 40.0 | | | | | | | 60.0 |

The composition of an alteration mineral may be determined by the composition of the invaded rock or of the invading fluid or a combination of the two but the mineral species will depend in part upon the temperature and other physical conditions. (See Table 5 for analyses of typical wall rocks and alteration minerals.)

If the wall rock is calcareous, the following may be expected: wollastonite, andradite, epidote, diopside, prehnite, vesuvianite, zoisite, calcite, or other lime-bearing mineral. Carbonate rocks, such as limestone, also, owing to the oxidizing effect of liberated

TABLE 5.

APPROXIMATE AVERAGE COMPOSITION OF WALL ROCKS AND METAMORPHIC MINERALS.[16]

| | $SiO_2$. | $Al_2O_3$. | $Fe_2O_3$. | FeO. | MgO. | CaO. | $Na_2O$. | $K_2O$. | $H_2O$. | $TiO_2$. | $P_2O_5$. | MnO. | $CO_2$. | $SO_3$. | C. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Granite | 73.9 | 12.5 | 1.6 | .8 | .2 | .9 | 3.9 | 4.8 | .5 | | | | | | |
| Monzonite | 53.5 | 15.6 | 3.4 | 5.3 | 4.3 | 7.6 | 3.5 | 4.3 | .9 | | | | | | |
| Diabase | 57.9 | 15.6 | .7 | 2.8 | 4.9 | 10.9 | 3.0 | 3.1 | .4 | .6 | .1 | .1 | | | |
| Andesite | 57.0 | 18.4 | 3.7 | 2.3 | 2.3 | 4.3 | 4.9 | 3.7 | 2.2 | .3 | .4 | .2 | | | |
| Gabbro | 48.2 | 18.2 | 1.2 | 6.1 | 10.8 | 9.4 | 1.3 | .7 | 2.0 | 1.0 | .1 | | | | |
| Shale | 58.1 | 15.4 | 4.0 | 2.4 | 2.4 | 3.1 | 1.3 | 3.2 | 5.0 | .6 | .2 | | | .6 | .8 |
| Sandstone | 78.3 | 4.7 | 1.1 | .3 | 1.1 | 5.5 | .4 | 1.3 | 1.6 | .2 | .1 | | 5.0 | | |
| Limestone | 5.2 | .8 | .5 | | 7.9 | 42.5 | | .3 | .7 | | | | 41.5 | .1 | |
| Chlorite | 32.0 | 15.0 | 1.6 | 2.5 | 34.0 | .3 | | | 13.0 | | | 1.2 | | | |
| Sericite | 51.0 | 31.5 | 2.5 | 1.0 | .7 | .3 | 1.0 | 9.0 | 4.0 | | | | | | |
| Augite | 43.0 | 12.0 | 10.0 | 2.5 | 12.0 | 20.0 | .3 | | | $Li_2O$ | | | $B_2O_3$ | F | |
| Hornblende | 38.0 | 38.0 | | 6.5 | .8 | | 1.5 | 1.5 | 3.5 | .2 | | 1.0 | 8.0 | .5 | |
| Tourmaline | 36.5 | 38.3 | .1 | 6.0 | 1.2 | .3 | 2.3 | .4 | 2.7 | 1.5 | | 1.0 | 9.5 | .6 | |
| Biotite | 37.0 | 15.0 | 3.7 | 15.0 | 15.0 | | 1.2 | 9.0 | 1.8 | | | | | 1.5 | |
| Vesuvianite | 38.5 | 15.5 | 4.0 | | 2.6 | 34.5 | .3 | | 2.4 | | | .7 | | | |
| Cordierite | 49.0 | 32.0 | | 6.7 | 10.0 | .2 | | | 1.5 | | | 1.0 | | | |
| Orthoclase | 64.5 | 18.0 | .2 | | | | 4.0 | 12.5 | | | | | | | |
| Albite | 68.7 | 19.5 | | | | | 11.8 | | | | | | | | |
| Pyroxene | 50.8 | 4.5 | .9 | 2.0 | 15.4 | 24.4 | .2 | .5 | 1.4 | | | .1 | | | |
| Diallage | 53.5 | 3.0 | 5.0 | 13.5 | 18.7 | 6.0 | .5 | .2 | | | | | | | |
| Uralite | 52.7 | 4.7 | 5.2 | 10.2 | 12.6 | 12.5 | .2 | | 1.5 | | | | | | |
| Epidote | 38.0 | 24.2 | 12.0 | | | 23.5 | | | 2.1 | | | | | | |
| Zoisite | 41.0 | 29.5 | 2.5 | | .5 | 23.0 | | .5 | 2.6 | | | | | | |
| Prehnite | 43.0 | 23.5 | 1.5 | | | 26.5 | | | 4.6 | | | | | | |
| Delessite | 30.5 | 16.8 | 3.2 | 15.5 | 18.5 | 1.2 | | | 14.0 | | | | | | |
| Ilvaite | 28.5 | | 23.5 | 28.5 | | 13.0 | | | 1.3 | | | 4.7 | | | |
| Grossularite | 40.0 | 22.7 | | | | 37.3 | | | | | | | | | |
| Andradite | 35.5 | | 31.5 | | | 33.0 | | | | | | | | | |
| Almandite | 36.2 | 20.3 | | 43.3 | | | | | | | | | | | |
| Diopside | 55.0 | | | .5 | 18.4 | 25.6 | | | | | | | | | |
| Tremolite | 57.6 | | | .8 | 26.0 | 15.0 | | | | | | | | | |
| Actinolite | 57.0 | 5.0 | | 1.0 | 21.0 | 16.7 | | | | | | | | | |
| Sillimanite | 36.7 | 57.9 | 4.4 | | .7 | .8 | | | | | | | | | |
| Andalusite | 36.8 | 63.2 | | | | | | | | | | | | | |
| Wollastonite | 50.0 | 3.5 | 1.5 | | .7 | 43.0 | | | .7 | | | | | | |
| Hedenbergite | 48.4 | | 20.4 | | | 22.2 | | | | | | | | | |
| Babingtonite | 50.0 | | 10.4 | 11.5 | 2.1 | 20.0 | | | .5 | | Cl | 4.6 | | | |
| Scapolite | 48.0 | 27.0 | | .1 | .1 | 16.0 | 4.6 | .7 | .8 | | 1.2 | | | | |
| Magnetite | | | 69.0 | 31.0 | | | | | | | | | | | |
| Hematite | | | 100.0 | | | | | | | $TiO_2$ | | | | | |
| Titanite | 30.6 | | | | | 28.6 | | | | 40.8 | | | | | |
| Rutile | | | | | | | | | | 100.0 | | | | $SO_2$ | |
| Alunite | | 37.0 | | | | | | 11.4 | 13.0 | | | | | 38.6 | |
| Ankerite | | | | 18.0 | 16.0 | 28.0 | | | | | | | 38.0 | | |
| Dolomite | | | | | 21.7 | 30.4 | | | | | | | 47.8 | | |
| Calcite | | | | | | 56.0 | | | | | | | 44.0 | | |
| Siderite | | | | 62.1 | | | | | | | | | 37.9 | | |
| Rhodochrosite | | | | | | | | | | | | 61.7 | 38.3 | | |
| Anhydrite | | | | | | 41.2 | | | | | | | | 58.8 | |
| Gypsum | | | | | | 32.5 | | | 20.9 | | | | | 46.6 | BaO |
| Barite | | | | | | Ca | F | | | | | | | 34.3 | 65.7 |
| Fluorite | | | | | | 51.1 | 48.7 | | | | | | | | |

[16] Tables 4 and 5 were compiled from Dana's System of Mineralogy, 6th ed., 1895 and U. S. Geol. Surv., Prof. Pap. 99, by H. S. Washington.

carbon dioxide, will precipitate, as magnetite or specularite, iron that may have come in with sulphur.

Aluminous rocks invaded by hypogene fluids may have developed in them sericite, andalusite, ilmenite, and many others. Intermediate rocks like monzonite and granodiorite are favorable hosts to sericite, chlorite, biotite, actinolite, hedenbergite, babingtonite, tourmaline, and others; and in basic rocks such minerals as chlorite, prehnite, datolite, analcite, and epidote may be expected.

Formerly it was customary to classify copper deposits as magmatic segregations, metasomatic replacements, fissure fillings (veins), and contact metamorphic deposits. Recent and more careful studies have shown that deposits like those at Sudbury and at Montecatini—long held by many to be magmatic segregations—are in reality replacements, and that all the known magmatic segregations of copper ores are small and unimportant. It seems probable, also, that contact metamorphic deposits are not emanations, or extracts, from local magma but that they owe their position to fractures produced either by shrinkage of the intrusive mass on cooling, or by crustal movements after the intrusive had solidified, and are essentially replacement deposits that have come from great depths through fractures. Lime silicates and other contact minerals are probably due more to the heat of the intrusive, which permits a reconstruction, under the new conditions, of the minerals in the adjacent sediments rather than to extracts from the magma itself. In any event there may be little or no copper metallization unless fracturing or shearing follows to open a passage down to the zone of the ore-bearing fluid.

Lindgren says on this subject, "Highly acid rocks, such as normal granites, are not always accompanied by ore deposits of the contact-metamorphic type, although they may produce widespread effects of metamorphism and a later mineralization of quartz veins." [17] And further, "The ore minerals are usually later than the silicates." [18] The evidence appears to justify the state-

[17] Lindgren, W.: Ore Deposits, 3d edit., p. 789, 1928.

[18] *Op. cit.*, p. 783.

ment that the important copper deposits are either veins or replacements, and that the latter may be either massive bodies or disseminations. Of 99 ore-bodies, in which the more important ones in the 81 districts are included, 23 are veins and 76 are replacements, 14 of which are disseminations.

The size of ore-bodies varies greatly. Veins occur in all sizes from microscopic veinlets to tabular bodies measuring several miles on the strike and a mile or more on the dip, which is generally steep, and a thickness that may be measured in tens of feet. Massive replacements are sometimes lenticular in form, but more often they are irregular in outline, conforming to the shape of the crushed, or otherwise more easily replaceable body of the invaded rock. Their maximum dimensions may approach those of veins but they are more nearly equidimensional. Disseminations of the "porphyry" type are large blanket-like bodies with irregular outlines. The horizontal dimensions may be thousands of feet and the vertical, hundreds of feet. Disseminations in beds of the Roan Antelope type are comparable to large veins. Many hypogene disseminations of the porphyry type are known but only a few without supergene enrichment are of commercial grade (Ajo); supergene enrichment brings them to commercial grade and also accounts for their blanket-like form.

Igneous intrusions, as has been observed, do not occur in all copper districts. Where they do occur, the usual order of intrusion is (1) salic magma, (2) mafic magma, and (3) sulphide mineralization. This sequence, since it is in the descending order of the magmas in the earth's crust, is suggestive that an escaping magma must be overlain by solid rock in which open fractures may be maintained. If open fractures reach only to the salic zone, salic magma escapes, if they reach through to the basic zone mafic magma rises, if they reach the sulphide zone ores ascend.

It is known from observation that sulphides rising toward the surface will replace practically every other mineral in their path if conditions are favorable. Also that copper sulphide will replace iron sulphide, the exact reversal of the reactions that took place as the fluid earth cooled down, and naturally so, because as

the ore-fluid surges up, the reactions take place in a rising temperature and are, therefore, endothermic, while those that took place in the cooling earth were exothermic. Let us assume that the released ore-fluid comes first to magnetite in the zone of oxides; the increasing heat dissociates the ions of the magnetite; the dissociated oxygen is seized by the rising sulphur and the volatile product is carried along with the current, leaving the iron to combine with other sulphur ions.

For reasons already stated it seems probable that no water exists in the ore-zone. Table 6 shows that water increases in

TABLE 6.

SHOWING THE INCREASE OF COMBINED WATER IN IGNEOUS ROCKS AS IRON INCREASES IN THE SILICATES, AND THE DECREASE IN WATER AS IRON-OXIDES INCREASE.

These are averages of many analyses compiled from U. S. Geological Survey Professional Paper 99 (1917), by H. S. Washington.

| Silica. | Iron oxides. | Water. | |
|---|---|---|---|
| 80–90% | 1.35 | .97 | |
| 70–80 | 2.03 | .84 | |
| 60–70 | 4.87 | 1.19 | |
| 50–60 | 4.59 | 1.36 | Silicates |
| 40–50 | 13.48 | 1.60 | |
| 30–40 | 16.07 | 2.19 | |
| 20–30 | 42.45 | 1.87 | |
| 10–20 | 55.65 | .81 | Oxides |
| 0–10 | 50.70 | .53 | |

igneous rocks as the water-bearing ferromagnesian silicates increase up to about two per cent, and that the oxides contain less than one per cent. When the mafic zone is invaded by the ore fluid and the silicates are broken down, the water of constitution of the silicates and other fluid or soluble compounds will be added to the moving stream, and, in the salic zone, the feldspars will yield soluble alkaline silicates that may contribute to the formation of metamorphic minerals, but, if carried toward the surface and meet ground water charged with carbon dioxide, the silica would be precipitated and the alkalies would go on in solution as carbonates. As the ore fluid moves toward the surface, the gradual reduction in temperature and pressure, with a possible change in chemical environment as well, would define the well-known concentric cones, zones, or halos favorable to the deposition of the

several ores and their associated minerals. At the onset of the rising fluid in the lower part of the column the action may be so vigorous as to dissolve the invaded rock, higher up conditions may be favorable to pyrogenetic deposition, and above that, metasomatic replacement, and still higher only deposition from solution. At the center of intensity of hypogene copper metallization one may find chalcocite, bornite, or chalcopyrite, and with them varying amounts of the usual non-copper-bearing sulphides.

Chalcopyrite is, by far, the most prevalent of the hypogene copper-bearing sulphides. It commonly persists to great distances outward from the center of mineralization. At its outer limits it gradually diminishes and finally stops whereas pyrite persists far out toward the limits of hypogene rock alteration. Metamorphic silicates and other alteration minerals accompany the sulphides and some, like chlorite and sericite, may continue far beyond the limits of pyrite, to the outward bounds of rock alteration, probably to the line where the temperature, during the period of mineralization, fell below the boiling point of water.

The alteration of ferromagnesian minerals to chlorite requires additional water. Biotite averages about three per cent water, amphibole about half as much, and pyroxene, still less, but chlorite contains 13 per cent. This additional water may be brought up from deeper seated ferromagnesian silicates in the manner already described. One cubic foot of gabbro, specific gravity 2.97, carrying two per cent water would yield 102 cubic feet of steam, which would probably be more than enough to convert the ferromagnesian silicates in a cubic foot of monzonite to chlorite.

The concentric zones, or halos, of alteration-intensity surrounding centers of mineralization do not remain fixed. They advance upward and outward, as the temperature is raised and the volatiles are diffused by the uprush of the mineralizing fluid. When sulphur invades the chlorite zone, pyrite replaces the chlorite, setting free its water of constitution, which escapes outward and upward into fresh country rock to extend the halo of chloritization. Chlorite, besides having more water than the mineral it replaces, has also more magnesium and less silicon and iron.

The extra magnesium may come from the country rock (if monzonite) or it may come along with the water released from deeper seated magnesium silicates. The silica discarded by the chlorite may be thrown out as quartz, and the iron may go into sericite, since the feldspar which it replaces contains no iron.

In general terms, then, it may be said that as the copper-sulphur fluid rises it reacts with the minerals of the invaded rock, converting the heavy metal oxides and silicates into sulphides, and releasing water, alkaline silicates, and other soluble compounds that permeate the terrane and react with the invaded minerals according to chemical and physical laws locally incident. During the transgressive stage the temperature rises and promotes endothermic reactions until the zenith is passed; when regression sets in, the temperature falls and chemical processes are reversed. Pyrite, which usually precedes chalcopyrite, being deposited at a lower temperature, may for the same reason follow it in the period of regression.

To recapitulate: The association of hypogene copper deposits with fractures or shear zones is universal. Copper sulphides replace practically every variety of rock; the intensity of the action depends upon the temperature, concentration, and pressure, and upon the chemical composition and physical condition of the invaded rock. Basic dikes next precede the ore in a large majority of the copper districts. This suggests that the ore came from beneath the basic magma after it was consolidated and fractured to permit the passage of the ore fluid. And it is at this abyssal depth that the ore would be concentrated under the influence of gravity and in accordance with the order of formation of exothermic compounds, if the earth at the beginning was a hot and fluid body like the sun.

3440 Clay Street,
San Francisco,
*July 16, 1940.*

# THE CHALCOCITE PROBLEM.

NEWTON W. BUERGER.

ABSTRACT.

A systematic x-ray study of the solid phases of the system $Cu_2S$–CuS has been made. A special camera was designed to make x-ray photographs of powder samples at elevated temperatures. This camera allows the specimen to remain heated continuously, and the heat treatment can be controlled as in a furnace. The resulting phase diagram shows that the system contains three compounds and four phases. The compounds are:

chalcocite, ideally $Cu_2S$
digenite, ideally $Cu_9S_5$
covellite, CuS.

Chalcocite undergoes transformation, and no cubic high temperature phase appears up to at least 300° C. The revised inversion scheme is:

above 105° C., hexagonal basic structure
below 105° C., orthorhombic superstructure.

The superstructure phase is capable of dissolving up to eight atomic per cent CuS, while the basic structure can dissolve only two atomic per cent CuS. Below approximately 78° C. digenite has the ideal composition $Cu_9S_5$, but above this temperature it takes increasing amounts of either $Cu_2S$ or CuS into its composition. Evidently digenite has been regarded as the phase of chalcocite stable above 91° C. Certain regions of the phase diagram of this system may be applied to problems of geologic thermometry, providing that proper criteria are recognized.

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## THE BACKGROUND OF THE CHALCOCITE PROBLEM.

*Early Investigations on the Transformations of Chalcocite.*—Chalcocite has long been held to be dimorphous. As far back as 1851, Hittorff (1) [1] investigated the effect of temperature on the electrical resistance of the mineral, and found that at about 103° C. there was a distinct change in the electrical conductivity. He also obtained cooling curves on two samples of chalcocite, and these showed pronounced effects in the region of 99° C. for one specimen, and 79° C. for the other. These cooling curves were made by simply heating the substance to, in this case, 200° C. and recording the time elapsed for it to cool to various temperatures. The results indicated a change of some sort at the temperatures mentioned.

Bellati and Lussana (2), in 1890, carried on similar experiments and obtained a temperature-time curve that showed an anomalous condition to exist at 103° C.

Some years later, 1903, Sahmen and Tammann (3:881) carried out a number of dilatometer measurements on various substances for the purpose of ascertaining inversion points. In view of the results obtained by Hittorff, they ran two cooling curves on chalcocite, and essentially duplicated the previous work; that is, their curves showed the same heat effect occurring between 78° C. and 80° C. Nevertheless, they could find no disturbance of the

[1] Numbers in parenthesis refer to Bibliography at end of paper.

rate of change of volume on dilatometer curves made on the same specimens, either on raising or on lowering of the temperatures. The method employed was capable of detecting volume changes of the order of 0.00012 cc. per gram.

In 1905, Mönch (4) made a study of the electrical conductivity of powder compacts of both natural and artificial chalcocites. In the case of the natural chalcocite (from Bristol, Connecticut) he found two breaks in the curve upon raising the temperature. One was in the form of a hump rising at about 95° C., reaching a maximum at 105° C., and falling back to normal at about 119° C. The other consisted of a steady, rather sharp rise beginning at 150° C. and more or less levelling off at 170° C. On lowering the temperature, the curve did not follow the same course; the drop began at 155° C. and levelled off at about 120° C., and the hump mentioned above did not show at all. On the other hand, the synthetic $Cu_2S$ gave an entirely different type of curve in which a change of slope was noted at 105° C., with another change occurring at 167.2° C. on raising of temperature. On lowering of the temperature the upper change came at 150° C., the lower again at 105° C.

Crystals having the approximate composition $Cu_2S$ are known to occur in an orthorhombic (pseudo-hexagonal) and an isometric modification (5: 135). The literature on this phase of the subject dates back to at least 1820, but is thoroughly reviewed by Groth (5: 143–145). Apparently, synthetic preparations of $Cu_2S$ give rise to the orthorhombic form at low temperatures, and to the isometric form at high temperatures.

Groth (5: 135) holds that an inversion from the orthorhombic chalcocite to the isometric type involves two substances that are structurally different, and which "possess, in any case, appreciably different densities." Such a density change, on transition, should be observed as a volume change, but the dilatometer measurements of Sahmen and Tammann indicate no such change in the region of 100° C. Therefore Groth doubts that the heat and resistance changes described by the investigators mentioned above are due to an inversion from orthorhombic to isometric modifications, but must be due to some other type of transformation.

The high temperature electrical effects recorded by Mönch were not confirmed by Reichenheim (6, footnote 28, p. 513), although the lower effect was obtained as occurring between 89° C. and 98° C.

*Extension of the Investigations to Compositions Between $Cu_2S$ and CuS.*—The first systematic study of the copper sulphides was published in 1915 by Posnjak, Allen, and Merwin (6). Only one heat effect, and the corresponding resistance change, was detected. This was correlated with an inversion from orthorhombic to isometric chalcocite for reasons to be mentioned subsequently. The temperature-time curves were obtained by means of a highly refined differential method. A summary of these curves (6, Table XIII) is reproduced in Table I.

TABLE I.

INVERSION TEMPERATURE OF PURE NATURAL AND SYNTHETIC CUPROUS SULPHIDE.

| Substance. | Heating. | Cooling. |
|---|---|---|
| Frederick Co., Md. | 91.5°C. | — |
| Bristol, Conn. | 90.0° | 86.5°C. |
| Butte, Mont. | 91.3° | 84.6° |
| Synthetic $Cu_2S$ I. | 90.7° | 88.0° |
| Synthetic $Cu_2S$ II. | 91.4° | 87.0° |

No other heat effects were observed up to 210° C., so that Mönch's second inversion at about 160° C. was not confirmed. It was found that the size of the grains apparently influences the inversion temperature; the coarser the grains, the higher is the inversion temperature.

Electrical conductivity measurements were also made in order to ascertain whether Mönch's upper (160° C.) transformation could be noted by this method. Sudden changes in resistivity occurred only at about 103° C., and no other was observed up to 200° C. The high value of the transformation temperature indicated by this method was attributed to the compactness of the material, since in this case powder compacts were used, whereas for the temperature-time curves, the material was in the form of loose powder.

The existence of a limited field of solid solution between $Cu_2S$ and CuS was also pointed out by Posnjak, Allen, and Merwin

(6: 506). A compact was made of $Cu_2S$–CuS powders in the proportion 9: 1, by weight. This was annealed at 110° C. for several hours and examined microscopically. It was found to be homogeneous throughout, so far as could be determined. This could be accounted for only by the solution of covellite in chalcocite. In order to determine how the inversion of chalcocite was influenced when covellite is present in solid solution, compacts of the desired composition were made, annealed, and crushed. Temperature-time curves made on this material gave the inversion temperatures shown in Table II (6, Table XV).

TABLE II.

INVERSION TEMPERATURE OF CUPRIC SULPHIDE-CHALCOCITE [SOLID] SOLUTIONS.

| Composition. | Temperature. |
|---|---|
| Inversion of $Cu_2S$ | 91.0°C. |
| 97% $Cu_2S$ + 3% CuS | 93.1° |
| 95% $Cu_2S$ + 5% CuS | 93.4° |
| 94% $Cu_2S$ + 6% CuS | 94.6° |
| Natural Chalcocite (5% CuS) | 93.3° |

With increasing CuS content, the amount of heat effect decreased, and preparations that contained eight or more per cent CuS showed no heat effect at all.

In order to substantiate that the inversion observed is one from the orthorhombic to isometric, the same authors (6: 520–22) attempted to form crystals above and below the inversion temperature of 91° C. Crystals formed in the dry way above 125° C. were determined to be isometric by their symmetry. Isometric crystals were also prepared from solutions, at 250° C. by one method, and above 125° C. by another method. It was found (6: 524–25) that low temperature chalcocite exhibits etch-cleavage parallel to the base, and also parallel to the front pinacoid, while the isometric high temperature form of cuprous sulphide shows no etch pattern. Cuprous sulphide containing more than about eight per cent cupric sulphide does not show the same etch pattern as chalcocite, but planes of octahedral parting show up more or less clearly.

Bateman and McLaughlin (7) and Per Geijer (8) noted the coexistence of chalcocite grains that gave isometric and ortho-

rhombic etch patterns, and suggested that this is due to original differences in dissolved covellite.

The next experimental work on the system $Cu_2S$–CuS was published in 1929 by Bateman (9). Natural crystals were used. It was found that even moderate temperatures within the range of 75° C. to 150° C. were sufficient to cause chalcocite to take covellite into solid solution. The solid solution field seemed to be limited by about 30 per cent to 40 per cent covellite in chalcocite. Covellite was also caused to unmix from solid solution in chalcocite, but the controls were not established, for the unmixing could not be made to occur at will.

Because of the importance of the $Cu_2S$–CuS system as a key to the origin of certain mineral deposits, Bateman and Lasky (10) subsequently investigated chalcocite relationships more thoroughly. The earlier conclusion that the solid solution takes place in one direction only, namely that covellite will dissolve in chalcocite, not the reverse, was confirmed. The temperature necessary for solid solution to take place was limited to between 70° C. and 75° C. Unmixing of covellite from solid solution was controlled by undercooling within a narrow range below this temperature. It would appear that the solution was only a surface phenomenon. No loss of sulphur was observed at any temperature below the decomposition point of covellite (358° C.).

*X-Ray Investigations of the Solid Phases of the System $Cu_2S$–CuS.*—Covellite has received three x-ray investigations. It was first studied by Roberts and Ksanda (11) who arrived at a complete structure determination on the basis of powder, Laue, and oscillating crystal photographs. About the same time, Alsen (12) also determined the space group using powder, Laue, and rotating crystal photographs. The crystal structure was finally investigated by Oftedal (13) who, on the basis of Laue, rotating and oscillating crystal photographs, arrived at the same cell and space group as Roberts and Ksanda, but suggested a different structure. Oftedal's structure is now accepted as being the correct one.

The structure of isometric chalcocite was first investigated by

Barth (14) who, with the aid of powder photographs taken at 200° C., suggested an antifluorite type structure. Shortly after this, Ramsdell (15) made powder photographs under unspecified conditions, and he, too, suggested an antifluorite structure.

Kerr (10: 69–72) made x-ray powder photographs of isometric chalcocite from Kennecott, Alaska, and states that "comparison of the measurements of the lines . . . with the chart for isometric crystals furnished by Hilger shows agreement with an isometric structure" with the exception of perhaps one line.

More recently considerable doubt has been cast on the earlier work on chalcocite. Rahlfs (16), in an extended study of $Cu_2S$-like compounds, made powder photographs of chalcocite at 170° C. He was unable to index his $Cu_2S$ photographs in terms of a cubic lattice. However, he found that $Cu_{1.8}S$ gave a cubic pattern, and that $Cu_{1.9}S$ gave rise to the lines of both the cubic and the non-cubic patterns. For the cubic $Cu_{1.8}S$, he derived a structure consisting of sulphur atoms at the points of a face-centered cubic lattice, with copper atoms statistically distributed over the several interstitial spaces. It might be pointed out in passing that this amounts to the antifluorite structure, in which the copper atoms are in complete disorder.

Rahlfs found that chalcocite from Bristol, Connecticut, at ordinary temperatures had the following cell dimensions:

| Cell. | Ratio. |
|---|---|
| $A = 11.8$ Å ..... | .435 |
| $B = 26.9$ ..... | 1. |
| $C = 13.4$ ..... | .498 |

Kurz (17) repeated Kerr's powder photograph of Kennecott isometric chalcocite with about the same results, and discussed the anomalous line. He also used a heating camera to make powder photographs at elevated temperatures. The material used was orthorhombic chalcocite from Messina. Photographs were made at temperatures of 20° C., 100° C., 125° C., and 200° C. He observed that the orthorhombic modification did not invert to a cubic modification above 91° C.

Orthorhombic chalcocite has also been investigated by Alsen

(12: 117) with material from Redruth and Bristol, by means of Laue, powder, and rotating crystal photographs. The cell of the orthorhombic modification was found to have the following dimensions:

| Cell. | Ratio. |
|---|---|
| $A$ = 11.8 Å | .434 |
| $B$ = 27.2 | 1. |
| $C$ = 22.7 | .834 |

This cell contains 320 copper atoms, and 160 sulphur atoms. The dimensions of the large cell can be described roughly in terms of multiples of the cell edge, $a$, of the cubic modification as follows:

| Orthorhombic. | | Cubic. |
|---|---|---|
| $A$ = .434 | $\approx$ | $2a$ = .400 |
| $B$ = 1. | | $5a$ = 1. |
| $C$ = .834 | | $4a$ = .800 |

It should be pointed out that Alsen's orientation differs from the crystallographic one adapted by Groth (5), the matrix of the transformation being:

Groth to Alsen

$$\begin{Vmatrix} 0 & 1 & 0 \\ 4 & 0 & 0 \\ 0 & 0 & 2 \end{Vmatrix}$$

It will be noted that Alsen's value for $C$ is considerably larger than that of Rahlfs'. Rahlfs suggests that perhaps Alsen measured the identity period along [102] instead of along [001] for the $C$ axis.

*Additional Possible Members of the System $Cu_2S$–CuS.*— Several minerals other than those hitherto designated as chalcocite and covellite, and which have possible places among the solid phases of the system $Cu_2S$–CuS, have been described in the literature. The first of these is the mineral digenite, described by Breithaupt (18) in 1844. One specimen was obtained from Sangerhausen, Thüringen, another from Chili. These appeared to have the composition $2Cu_2S.CuS = Cu_5S_3$. A related material called carmenite was described by Hahn (19) from Carmen Island, Gulf of California, which appeared to have the composition $Cu_2S.CuS = Cu_3S_2$. Material of the same composition was

subsequently described from Sunnerskog by Lindström (20). Due to Dana's detection of some covellite in a sample of carmenite, both carmenite and digenite apparently have been discredited as mineral species.

## EXPERIMENTAL WORK WITH CONTROLLED-TEMPERATURE CAMERA.

A preliminary survey of the solid phases in the system $Cu_2S$–CuS at room temperature (25) has shown the existence of a third compound, $Cu_9S_5$, in addition to the two end members $Cu_2S$ and CuS. This intermediate compound corresponds with the mineral digenite.

The existence of $Cu_9S_5$ put the chalcocite problem in an entirely new light. It now seemed highly desirable to make a detailed study of the temperature-composition phase fields of the system. Two methods were available to obtain the desired x-ray information on these phases at elevated temperatures:

(1) by heating the sample to the desired temperature and then rapidly quenching to room temperature, the powder photograph being taken at room temperature; or,

(2) by using a controlled-temperature camera, in which the material is heated in the camera to the desired temperature, and the photograph taken while the specimen is maintained at that temperature.

The first method is commonly employed by metallurgists to obtain phase diagrams of alloys, but it assumes that the material is capable of retaining the high temperature phase on quenching. In such cases there is always some doubt that the substance actually did not behave in the sluggish way assumed. To avoid this doubt, the controlled-temperature method was chosen. Since available instruments did not entirely meet the requirements of the problem, a camera was designed which was a departure from the conventional types.

### *The Controlled-Temperature Camera.*

*The Heating Unit.*—Much time and experimentation was devoted to the development of the correct type of heating unit em-

ployed in the camera, since it is one of the most important parts of the apparatus. The unit finally used consists essentially of a miniature electric furnace which is slipped into place in such a way that the specimen mount is completely enclosed by it. A slit in the furnace container allows the x-ray beam to go through to the specimen and be diffracted to the film.

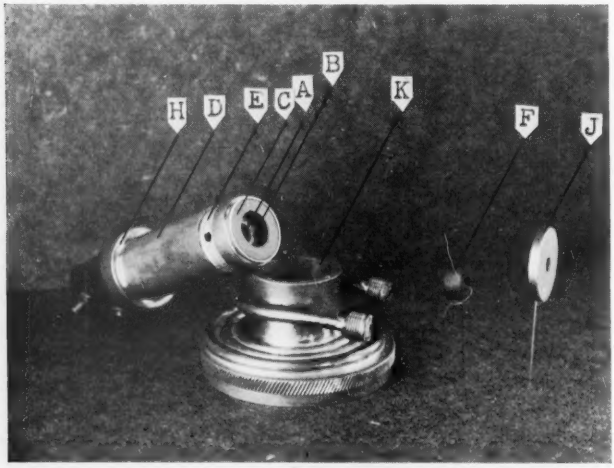



FIG. 1. Detail of furnace unit.

The heating unit (Fig. 1, *A*) consists of a coil of six turns of No. 24 B. & S. gauge chromel "A" resistance wire. This was made by winding a helix on the shank of a No. 1 twist drill, giving an inside diameter of the coil of about 5/16". The coil was pulled apart slightly so that none of the turns touched, and then the third and fourth turns were separated further in order that they would not obstruct the slit (*E*) through which the x-ray beam is allowed to enter and emerge. The coil, excluding the leads, is about 10 mm. long.

The furnace proper, shown on the left in Fig. 1, consists essentially of three hollow coaxial cylinders that nest one within the other. The first, or outer cylinder (*D*) is made of brass and fits

snugly around a fiber cylinder (*C*). The third (*B*) is a small "Transite" cylinder about 12 mm. long that encloses the heating coil. A hole is drilled through the fiber, axially, in order that a thermo-couple may be inserted into the furnace. The end containing the heating unit is closed by a fiber plug (*F*) over which is fitted a brass cap (*J*); through both of these is a hole about 3/32" in diameter, which allows the specimen to be inserted into the furnace.

A slit (*E*), which permits the x-ray beam to enter the furnace chamber, and be diffracted by the specimen to the film, is milled through the brass, fiber, and transite cylinders. The slit is covered with aluminum foil, for a double purpose: it allows the x-rays to pass through, but does not permit the radiant heat from the furnace to be dissipated through it. There are two holes in this aluminum foil filter, one at the x-ray beam entrance port, the other at the exit port; this permits the beam an unimpeded path so that there is no diffraction pattern produced by the aluminum.

The whole furnace thus is encased in brass, and is introduced into the camera through a sleeve that is integral with the cover (*K*). This automatically assures perfect alignment of the camera and furnace axes. A stop ring (*H*), in which is set a guide pin, is attached to the furnace and further assures the exact positioning of the furnace each time it is slipped into the camera.

In order to keep the film from being effected by the heat of the furnace, the camera is water-cooled by means of a coil of copper tubing soldered onto the cover.

It should be pointed out here that the selection of the materials for the furnace was definitely restricted by those available at the time. Experience gained during the course of the experimental work that followed, showed that some material other than fiber might have been used to better advantage for the purpose of supporting the heating unit.

*The Camera.*—In the design of the camera itself, provision was made for the external loading and unloading of the film. In order to do this, and still retain a simple design, the film is protected from light by enclosing it in a black paper envelope.

Some important constructional features of the camera (Fig. 2) are as follows: The film envelope is seated on a recessed face that is carefully machined to be concentric with the axis of rotation of the specimen. The recess assures proper positioning of the film. The x-rays strike the film through a slot, which is milled down the

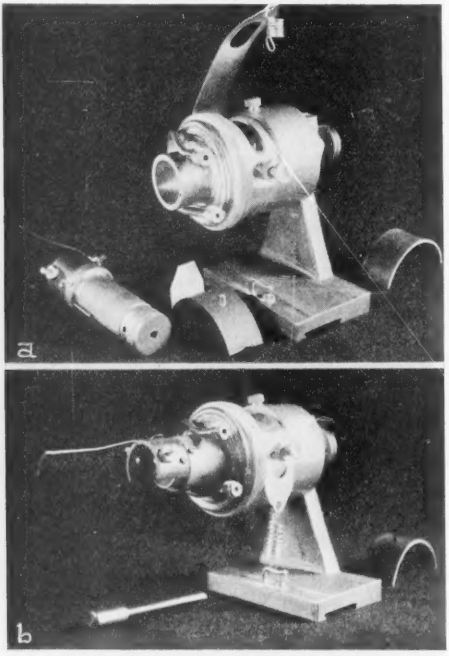



FIG. 2*A*, 2*B*. Detail of controlled-temperature camera.

center of this face so as to allow as much as possible of the diffracted beam to be recorded on the film between the entrance and exit ports. The film in its envelope is held firmly against the face by means of a thin strip of phosphor bronze, which is kept under tension by a coil spring fastened to the camera base.

The body cylinder of the camera has been made long enough

to provide room for withdrawing the specimen from the furnace at any time that it is desired to insert the thermocouple into the furnace for a temperature determination. This is done by simply removing the rubber driving belt from the spindle and moving the spindle until the specimen is out of the furnace chamber.

Because the inside diameter of the camera is quite small, the centering screws cannot be adjusted with the fingers in the usual way without running the risk of breaking the capillary mount. Therefore a hole has been provided through the top of the camera body so that a small screw driver may be inserted for making the necessary adjustments. The camera is shown in detail in Fig. 2.

*Determination of Temperature Within the Furnace.*

In order to determine accurately the temperature within the furnace, a copper-constantan thermocouple was initially used in conjunction with a potentiometer and an ice bath zero point. Several devices for temperature determination were tried, including many types of thermometers and a chromel-alumel thermocouple, but these were rejected because of their insensitivity. The copper-constantan couple proved to be extremely sensitive, reflecting, almost instantaneously, minute changes of current flowing through the heating coil, in terms of millivolts. A Leeds & Northrup semi-precision type potentiometer was used for measuring the e.m.f. produced by the couple.

Subsequent work on the calibration of controlled-temperature cameras (26) has shown, however, that temperatures determined by the method outlined above are in error. This error is due chiefly to the conduction of heat from the thermocouple junction by the wires of the thermocouple. A method has therefore been devised which makes use of various polymorphous substances of known transformation temperatures. Such a substance, for example, is ammonium nitrate, $NH_4NO_3$, which has several inversions. The material is simply mounted in the camera and a series of powder photographs taken at known energy input to the heating element. The transformations are readily noted in the photographs, and a temperature-energy calibration chart may be plotted. This method has been employed in the present work.

*Source of Current for Furnace.*

To maintain a constant temperature in the furnace the current must be absolutely unfluctuating. The ordinary power line current, both alternating and direct, was found to be entirely unsatisfactory for this purpose. Two Willard GLWR4, 150 ampere hour, radio type storage batteries connected in series were therefore used to supply the current for the furnace unit. This proved to be entirely satisfactory. Perfectly constant temperatures could be maintained during runs lasting as long as forty consecutive hours, providing the batteries were recharged between runs.

The current to the furnace is varied by means of two resistances in series with the batteries. One of these is a slide wire type, and is used for the coarse adjustment. Very fine adjustment is accomplished by the use of a carbon pile type resistance.

*X-Ray Tube and Equipment.*

A standard Philips Metalix rayproof research type, hot-cathode, copper anode tube was used for the source of x-radiation. Cu K$\alpha$ radiation was obtained from this by filtering through nickel foil .001 inch thick. Built into the design of the support for the base of this tube is a camera platform that is provided with a dovetail slide arrangement by means of which the camera always recovers exactly the same position, thus assuring identical exposure on each photograph. The specimen is constantly rotated during a run by means of a Telechron motor, built into the camera platform, which drives the specimen spindle through a rubber belt. The exposure time in all photographs was one hour, with the tube operating at 30 milliamperes and 27 kilovolts, unrectified.

*Method of Making Specimens.*

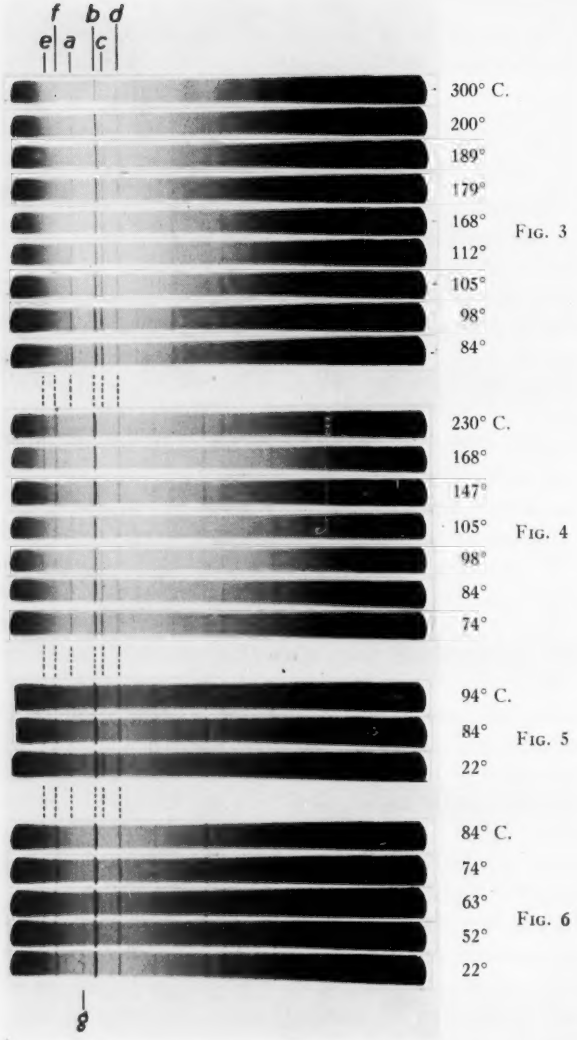
The method of making the specimens used in this study consists essentially of three steps: (1) making a compact of the material, (2) annealing the compact, and (3) mounting the material. The end member material is described elsewhere (25).

Pure natural chalcocite from Bristol, Connecticut, was used for the $Cu_2S$ member, and synthetic CuS for the other.

*Compaction.*—The powders used were carefully weighed out on a chemical balance so that each sample weighed one gram. This was put into a small vial. Several vials at a time were thoroughly mixed by mechanical rotation for about four hours. Each sample was next compacted into small rods about 3/8" long, and 1/4" in diameter. The compacting die consists of a hardened steel cylinder 1 1/4" long with a 1/4" hole through it; into this fit two pistons, one about 1/4" long, the other 1 1/4" long. In making the compact, the small piston is placed at the bottom of the hole, the powder poured into the hole, and the long piston pressed down on the powder. The die is transferred to a hydraulic press and subjected to a pressure which is equivalent to about 14,000 atmospheres. The long piston may finally be pushed through, forcing the compact out.

*Annealing.*—Each compact was placed in an open glass tube and annealed in an electric furnace at a temperature of about 110° C. for a period of at least 12 hours. After being annealed, the compacts were crushed, recompacted, and reannealed in order to assure complete homogeneity within the sample.

*Mounting.*—As insurance against any chemical change taking place in a sample exposed to elevated temperatures, a method of mounting the material was developed in which the sample, in the form of very fine powder, is entirely sealed within a very thin-walled capillary tube. For this purpose, capillary tubes were drawn from pyrex glass tubing initially having an outside diameter of about 20 mm. and walls about 1.5 mm. thick. The resulting capillary tubes have an outside diameter of approximately 0.02 inch and are about 18 mm. long. One end of the capillary is first sealed, and the tube is then filled with the powder to within about a millimeter from the unsealed end. This end is finally sealed by holding it in an intense oxygen flame for an instant. This type of specimen mount has proven extremely satisfactory, and has been one of the most important factors in the successful outcome of this investigation.




FIGS. 3–6. Powder photographs of, 3, Chalcocite; 4, 95 per cent $Cu_2S$ + 5 per cent CuS; 5, 90 per cent $Cu_2S$ + 10 per cent CuS; 6, 86 per cent $Cu_2S$ + 14 per cent CuS.

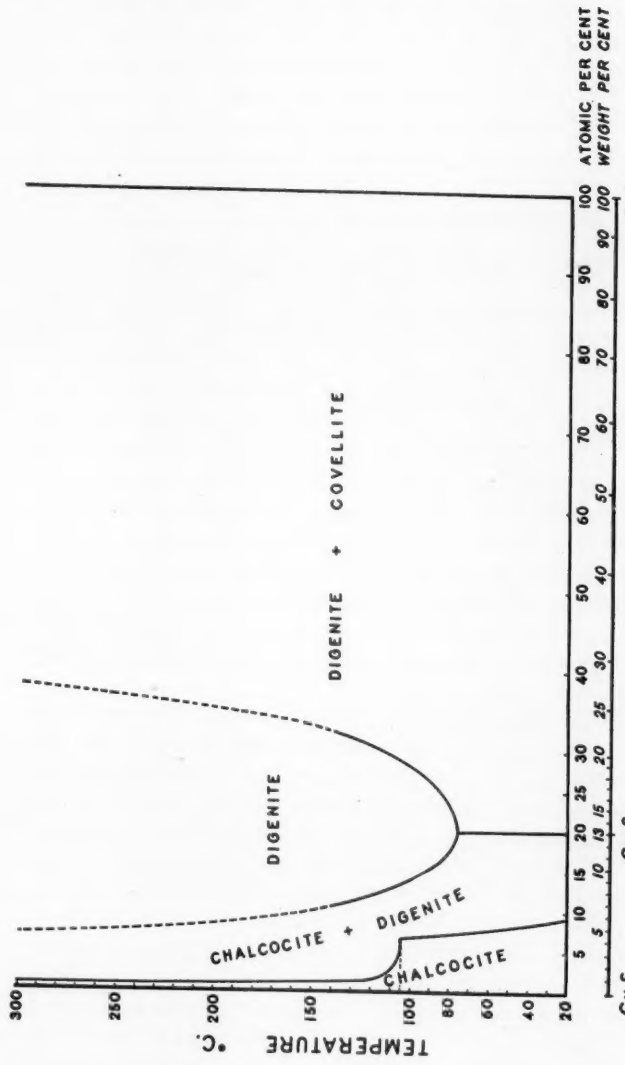



FIG. 7. Phase diagram of the system $Cu_2S$–CuS.

The manner in which the specimen tube is secured to the mounting pin is slightly different from that usually employed (21: 15–16) since the mounting capillary has to be held to the pin without the aid of a cement, which might melt at high temperatures. The specimen tube is held in a groove on a flattened surface of the pin by means of a small spring attached to the pin. The loaded pin is then inserted into the centering chuck of the camera, and secured by a set screw.

*Determination of Phase Field Boundaries.*

After the developmental stage of the work had been completed, some two hundred controlled-temperature powder photographs were made using the apparatus and methods just described. Of these, about 160 were actually used in obtaining the phase diagram shown in Fig. 7, the remaining photographs being accounted for by cut-and-try development of the necessary technique, and other runs exploratory and confirmatory in nature. It is unnecessary to give a detailed discussion of the various photographs made to more or less feel out the problem of determining a phase diagram by this new and rather novel technique. Certain fundamental experience was gained from a careful study of the initial photographs, chief of which was the development of criteria used in the actual determination of the phase field boundaries.

There are three phases in the system $Cu_2S$–CuS that were found to appear at room temperature, namely chalcocite, digenite, and covellite (25). These phases give rise to characteristic diffraction patterns. Certain of the more intense lines of these patterns lend themselves as indicators of the presence of that particular phase in the photographs obtained in this study. In a one-phase field, of course, only one set of lines is present; but in a two-phase field there are two sets of lines present, one set from the one phase, and another set from the other phase. As a two-phase field is traversed towards its boundary with a one-phase field, the lines characteristic of the phase field being approached gradually increase in intensity at the expense of the lines of the other phase, whose lines correspondingly decrease in intensity.

This traversing of a two-phase field towards, and finally into a one-phase field is illustrated in Figs. 4, 5, and 6, in which a temperature path is being followed upward along a vertical fixed composition line. Figure 5 illustrates photographs of a specimen of the composition, by weight 90 per cent $Cu_2S$ + 10 per cent CuS as the temperature is raised. It will be noted that the characteristic lines of chalcocite, *a* and *c*, decrease in intensity, on raising of temperature, while the characteristic lines of digenite, *e* and *f*, increase, until finally at 94° C. the chalcocite lines *a* and *c* vanish, showing that the digenite one-phase field is entered. Figure 4 shows the same general sequence of changes occurring in a specimen of the composition 95 per cent $Cu_2S$ + 5 per cent CuS. In this case, however, the digenite one-phase field is entered between 168° C. and 230° C. A series of photographs of a specimen of the composition 86 per cent $Cu_2S$ + 14 per cent CuS is shown in Fig. 6, illustrating the same type of change, but in this instance the two phases involved are covellite, characterized by line *g*, and digenite, characterized by lines *e* and *f*. The digenite field is entered here between 74° C. and 84° C.

The criteria used in fixing the inversion point of pure chalcocite may be seen in the series of photographs illustrated in Fig. 3. Examination of the photographs taken at 105° C. and above shows that they are characterized by a comparatively simple pattern of relatively few lines. This basic pattern is retained by chalcocite at all temperatures, but at temperatures below 105° C. there are, in addition to these basic lines, many weaker ones. Attention is particularly directed to those in the region to the left of line *a*. This is the region of low $\theta$ values, and lines here are indicative of a large cell, which is a multiple of the smaller one indicated above 105° C. by an absence of lines in the low $\theta$ region.

## DISCUSSION OF RESULTS.

*The Polymorphism of Chalcocite.*—Because the chalcocite pattern changed near 105° C., while earlier investigators had found pronounced heat and electrical effects in the region of 91° C., the writer inferred that his material might not be identical with that used by the other investigators. To check this, the

same material was tested independently on precise apparatus for recording thermal effects. The writer is indebted to Drs. Earl Stevenson, Walter Smith, and Normal Johnston, of Arthur D. Little, Inc., for carrying out this part of the investigation on their apparatus, which essentially records the rate of absorption of heat

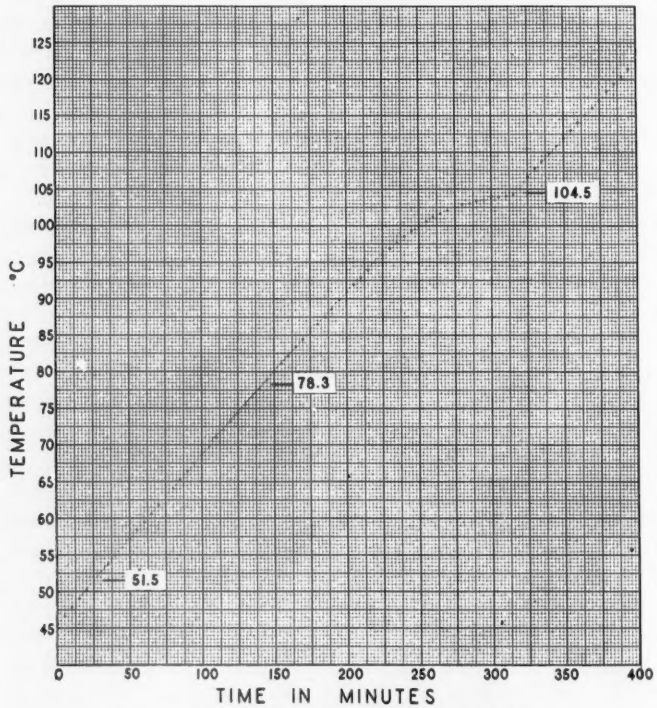



FIG. 8. Temperature-time curve for chalcocite.

by the material being tested. The method is unusual in that the bath in which the specimen is immersed is automatically maintained 5° C. above that of the specimen. The data resulting from this test are presented in the form of a graph in Fig. 8. Careful examination of the graph shows that the portion up to

52° C. is a straight line, and the portion from 52° C. to 78° C. is also a straight line, but the portion between 78° C. and 105° C. is a *curve* whose slope decreases more and more rapidly until about 105° C.; above this the graph again resumes its course as a straight line.

It is evident that the 105° C. break in the graph indicates an inversion and corresponds with the superstructure-to-basic-structure inversion placed by x-ray data at about 105° C. The only explanation for the gradual change in the portion of the graph between 78° C. and 105° C., coupled with the fact that there is only a minor change in certain intensities in the powder photographs in this region, is that this range corresponds with a gradual transition (22), (23), (24).

In view of this conclusion, it is of interest to re-examine the characteristics of the heat effects found by Posnjak, Allen, and Merwin (6, Fig. 76). Their curve for coarse chalcocite powder is almost identical in shape with that of the specific heat curve for $Cu_3Au$ (24, Fig. 34) or for certain brasses (24, Fig. 36). Furthermore, the curve of Posnjak, Allen, and Merwin departs from a straight line at 78° C. and attains a peak in the region of 104° C. This corresponds exactly with the new heating data just mentioned. There is thus every evidence that chalcocite begins to become disordered at 78° C. and attains complete disorder at about 105° C.

The peculiar distorted heating curve shapes found by Posnjak, Allen, and Merwin for finely ground powder are very interesting. They are evidently abnormal due to the partial destruction of the crystalline structure of the chalcocite by the fine grinding; chalcocite is quite plastic. These authors placed great reliance on curves obtained with fine powders, and consequently placed the inversion at 91° C. instead of 104° C.

The status of the polymorphism of chalcocite may be summarized in the following form: Between room temperature and 250° C., chalcocite exists in two modifications, connected by a gradual transition. These chalcocite modifications and their stability fields are:

| Stability Region. | Structural Characteristics. |
|---|---|
| Above 105°C., | hexagonal[2] basic structure |
| Below 105°C., | orthorhombic superstructure |

*The Phase Diagram of the System $Cu_2S$–CuS.*—On the basis of the critical examination of some 160-odd powder photographs, together with the conclusions arrived at in the previous sections, the phase diagram of the system $Cu_2S$–CuS was determined, and is reproduced in Fig. 7. The system displays three compounds, four phases, and six phase fields.

The compounds are:

Chalcocite, ideally $Cu_2S$
Digenite, ideally $4Cu_2S.CuS = Cu_9S_5$
Covellite, CuS.

The phases are:

High chalcocite
Low chalcocite
Digenite.
Covellite.

The phase fields shown in the diagram are:

Three single phase fields corresponding to the phases outlined above, except covellite.
Three duplex phase fields:
digenite + high chalcocite
digenite + low chalcocite
digenite + covellite.

*Solid Solutions.*—Low chalcocite is capable of dissolving up to about eight atomic per cent CuS, while the high chalcocite can dissolve very little CuS.

Below about 78° C., the compound digenite has the ideal composition $Cu_9S_5$, but above this temperature it takes increasing amounts of either $Cu_2S$ or CuS into its composition. At 170°

[2] The writer, in recent x-ray studies by the Weissenberg equi-inclination method, has shown that chalcocite above 105° C. is hexagonal. Results of this work will be published shortly.

C., it is known from the crystal structure study of Rahlfs (16: 191) that what is now known to be digenite has an antifluorite structure in which the Cu atoms are in disorder.. Since the structure positions are tolerant to the presence or absence of Cu atoms, as evidenced by disorder, the mechanism of the compositional variation (*i.e.*, solution of $Cu_2S$ or CuS) is undoubtedly a variation in the number of Cu atoms in the crystal structure. It is possible that at a temperature of 78° C. or lower, the Cu atoms become ordered and give rise to another digenite phase.

*Discussion of Certain Anomalies.*—Posnjak, Allen, and Merwin (6: 518–520) remarked that the heat effect which they investigated persisted for specimens up to six per cent, by weight, CuS, but that the heat effect vanishes for specimens containing eight per cent or more. The phase diagram gives a ready explanation of this. A sample containing about ten per cent passes through the two-phase field chalcocite-digenite, but, before the chalcocite is able to produce its major thermal effect at 104° C. it has already been completely converted to digenite.

When chalcocite is heated *in direct contact with air* it begins to convert to digenite. This was discovered in the early stages of this research, during the development of the correct type of specimen mount. When the powdered material is held on the *outside* of a capillary, by means of a suitable adhesive, this conversion takes place during heating, whereas when the material is sealed *inside* the capillary, out of contact with air, no such effect can be produced. It appears, then, that oxygen can proxy for sulphur, and that heating the chalcocite in air has much the same effect as would be obtained if the material were heated in sulphur vapor, namely, the composition of the specimen is changed to a higher atomic (S, O) content, *i.e.*, lower Cu content. *Such a specimen, on heating, follows a path moving upward and to the right in the phase diagram, Fig. 7, passing from the pure chalcocite field into the duplex chalcocite-digenite field, and finally into the single-phase digenite field.* A number of investigators have thus probably obtained anomalous results because they worked with chalcocite specimens exposed to air. This would, for ex-

ample, explain why Barth (14) suggested an antifluorite structure for chalcocite heated to 200° C.

It will be recalled that Mönch (4) obtained an electrical resistance curve for chalcocite which showed a break in the region of 100° C., and another at about 160° C. on raising the temperature, while only the upper effect was noted when the temperature was lowered. This is quite in agreement with the observations noted above. The chalcocite, on being heated in air, would follow a path leading diagonally upward to the right towards the digenite field, but, on cooling, would probably more or less follow a constant composition path; in any case, the downward path need not be the same as the upward path if the material is heated in air.

*Application of the Phase Diagram to Geological Thermometry.*—The use of any mineral in the system $Cu_2S$–CuS as a guide to the geological history of the deposit in which it is found should be based on the understanding and application of the phase relations of the system. For example, if a crsytal of digenite is found containing unmixed covellite, it can be studied for implications as to its temperature of formation. A series of controlled-temperature powder photographs might be made, and the temperature determined at which the covellite vanishes. The crystal could not have been formed at a lower temperature than this. This, of course, presupposes a recognition of unmixing structures.

A mixture commonly found in nature is low chalcocite and digenite (so-called white and blue chalcocite). If a specimen of this kind showed no unmixing structure, it could have been formed at any temperature, but, on the other hand, if an unmixing structure were shown, a sample of the specimen could then be heated in a controlled-temperature camera. The photographs will indicate the crossing of the two-phase field, and eventually will show only digenite lines. The temperature at which the digenite field is entered is the minimum temperature of formation of the specimen.

ACKNOWLEDGMENTS.

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*June 10, 1940.*

REFERENCES.

1. HITTORFF: Ueber das electrische Leitungsvermögen des Schwefelsilbers und Halbschwefelkupfers. Ann. Phys. u. Chem., 84: 1–28, 1851.
2. BELLATI, M., UND LUSSANA, S.: Ueber die specifische und Umwandlungswärme von Schwefel- und Selensilber, Schwefel- und Selenkupfer. Atti Instit. Venet. (6), 7: 1051, 1880. Abst. in Zeits. Krist., 23: 167–170, 1894.
3. SAHMEN, R. V., UND TAMMANN, G.: Ueber das Auffinden von Umwandlungspunkten mit einem selbstregistrierenden Dilatographen. Ann. der Phys. (4), 10: 881, 1903.
4. MÖNCH, WILLY: Ueber die elektrische Leitfähigkeit von Kupfersulfür, Silber-, Blei-, und schwartzem Quecksilbersulfid. Neues Jahrb. f. Min. etc., B. B. 20: 365–435, 1905.
5. GROTH, P.: Chemische Kristallographie. 1: 135, also 143–145, 1906.
6. POSNJAK, EUGENE, ALLEN, E. T., AND MERWIN, H. E.: The sulphides of copper. ECON. GEOL., 10: 491–535, 1915.
7. BATEMAN, ALAN M., AND MCLAUGHLIN, D. H.: Geology of the ore deposits of Kennecott, Alaska. ECON. GEOL., 15: 1–80, 1920.
8. GEIJER, PER: Some Swedish occurrences of bornite and chalcocite. Sver. Geol. Und., Ser. C, 321, Ars. 17: 2, 42–43.
9. BATEMAN, ALAN M.: Some covellite-chalcocite relationships. ECON. GEOL., 24: 424–439, 1929.
10. BATEMAN, ALAN M., AND LASKY, SAMUEL G.: Covellite-chalcocite solid solution and ex-solution. ECON. GEOL., 27: 52–86, 1932.
11. ROBERTS, H. S., AND KSANDA, C. J.: The crystal structure of covellite. Amer. Jour. Sci., (5) 17: 489–503, 1929.
12. ALSEN, NILS: Ueber die Kristallstrukturen von Covellin (CuS) und Kupferglanz ($Cu_2S$). Geologiska Föreningens I Stockholm Förhandlingar, 53: 111–120, 1931.
13. OFTEDAL, I.: Die Kristallstruktur des Covellins (CuS). Zeits. Krist., 83: 9–25, 1932.
14. BARTH, TOM: Die reguläre Kristallart von Kupferglanz. Central. für Min. etc., A, 1926: 284–286.

15. RAMSDELL, LEWIS C.: The crystal structure of cuprous sulfide. Amer. Min. 13: 115, 1928.
16. RAHLFS, PAUL: Ueber die kubischen Hochtemperaturmodifikationen der Sulfide, Selenide und Telluride des Silbers und des einwertigen Kupfers. Zeits. für phys. Chem. (B) 31: 157–194, 1936.
17. KURZ, WOLDEMAR: Chemisch-röntgenographische Untersuchung am "blauen Kupferglanz." Zeits. Krist., 92: 408–434, 1935.
18. BREITHAUPT, AUGUST: Zwei neue Kupfer enthalende Mineralien aus der Ordnung der Glanz. Ann. Phys. u. Chem., 61 (ser. III, 1): 671–675, 1844.
19. HAHN, H.: Carmenit, ein neues Mineral. Berg und Hüttenmännische Zeitung, 24: 86, 1865.
20. LINDSTRÖM, G.: Analys af ett kopparmineral från Sunnerskog. Geologiska Föreningens I Stockholm Förhandingar, 7: 678–680. 1885.
21. BUERGER, M. J.: An x-ray powder camera. Amer. Min., 21: 11–17, 1936.
22. KRACEK, F. C.: Gradual transition in sodium nitrate. I. Physico-chemical criteria of the transition. Jour. Amer. Chem. Soc., 53: 2609–2624, 1931.
23. BUERGER, M. J.: The temperature-structure-composition behavior of certain crystals. Proc. Nat. Acad. Sci., 20: 444–453, 1934.
24. NIX, FOSTER C., AND SHOCKLEY, WILLIAM: Order-disorder transformations in alloys. Rev. Mod. Physics, 10: 1–71, 1938.
25. BUERGER, NEWTON W.: An x-ray investigation of the solid phases of the system $Cu_2S$–CuS. Unpublished thesis, Department of Geology, Massachusetts Institute of Technology, 1939.
26. BUERGER, M. J., BUERGER, NEWTON W., AND CHESLEY, FRANK G.: Apparatus for taking x-ray powder photographs at controlled, elevated temperatures. In preparation.

# MINERALOGY OF THE NEGUS AND CON MINES, YELLOWKNIFE, NORTHWEST TERRITORIES, CANADA.

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ABSTRACT.

The Con and Negus are two gold mines near Yellowknife with ore running between $30 and $40 to the ton, and contain-

ing much visible gold. The lode deposits consist of quartz-carbonate veinlets that follow zones of shearing in pre-Cambrian andesites. The mineralogy is complex. There are sulphides, arsenides, antimonides, and many uncommon minerals including gudmundite. They suggest intermediate temperature deposition. Textures and structures suggest low pressure deposition. It is concluded that the deposits may be expected to persist to a depth of several thousand feet or more, providing the structural control continues in depth. It is intimated that the shear zones should be found at great depth as they are presumably related to a neighboring tear fault with a 5-mile horizontal displacement. Structures of this magnitude suggest, further, that the Yellowknife field may become an important mining district.

## INTRODUCTION.

*Location.*—Yellowknife bay is one of the many indentations in the north shore of Great Slave lake, in the Northwest Territories of Canada (Fig. 1). The townsite of Yellowknife lies on the west side and near the head of the Bay (Fig. 2). The Con mine is located nearly 2 miles south of the townsite, and the Negus immediately south of the Con.

*The Properties.*—These two mines are the first gold producers of the district. The Con, a unit of the Consolidated Mining and Smelting Company of Canada, began production in September, 1938. The Negus, owned by Negus Gold Mines, Limited, poured its first gold brick in February, 1939. The ore of both mines is reported to run between $30 and $40 to the ton.

*Acknowledgments.*—During the summer field season of 1938, the writer assisted Dr. A. W. Jolliffe in the detailed mapping of part of the Yellowknife Bay quadrangle for the Geological Survey of Canada. The investigation of the ores of the Negus and Con mines was suggested to the writer by Professor Edward Sampson and the work was carried on under his direction in the laboratories of the Department of Geology, Princeton University. The writer is much indebted to Professor Sampson for his assistance and suggestions, and for reading the manuscript.

To Dr. A. W. Jolliffe the writer is extremely grateful for making this study possible, and for unhesitatingly supplying material, maps, and information.

The writer wishes to thank Mr. J. R. Giegerich of the Consolidated Mining and Smelting Company and Mr. A. E. Kipps

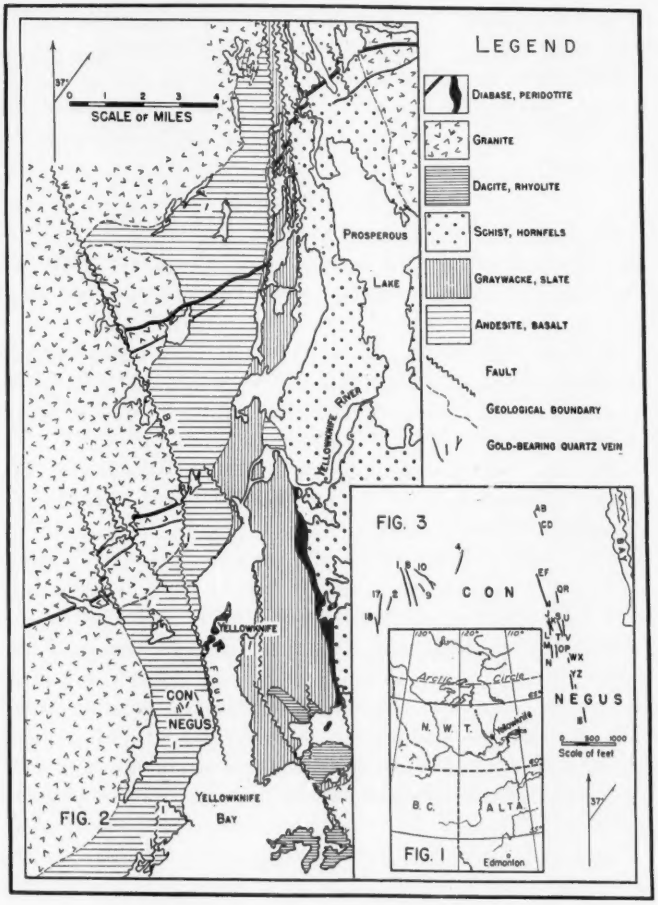



FIG. 1. Index map showing location of Yellowknife, N. W. T., Canada.

FIG. 2. Generalized geological map of Yellowknife bay and vicinity showing fault system (after the Geological Survey of Canada).

FIG. 3. Sketch showing the surface exposure of the mineralized zones of the Negus and Con mines. Zone identification is the same as that used by Jolliffe, 1938.

of the Negus Gold Mines for the many courtesies extended to him while collecting specimens on their respective properties.

The writer is indebted to M. H. Haycock and the Mines Branch, Ottawa, for the mounted and excellently polished sections; and the Geological Survey, Ottawa, for the loan of certain specimens.

## GENERAL GEOLOGY.

The following brief account of the geology of the Negus and Con properties is based on published information by A. W. Jolliffe[1] and information gained personally by the writer while visiting these properties.

The rock types consist of basic flows and dikes, a single granite outcrop, a few aplitic dikes, late diabase dikes, and mineralized shear zones. All are of pre-Cambrian age with the possible exception of the latter two.

*The Basic Volcanics.*—The volcanics—andesites—are fine-grained, dark-green, and fairly homogeneous. They contain some pillow structures that are elongated uniformly east-northeast. Dips are nearly vertical, and the younger flows lie to the southeast.

*The Early Basic Dikes.*—The volcanics are cut by early basic dikes of similar composition and texture. A hand specimen of a dike cannot be distinguished from a hand specimen of a flow and the chilled contacts of the dikes are very difficult to see and trace. The dikes trend at about right angles to the east-northeast strike of the flows, and were possibly feeders for the younger, overlying flows to the southeast. These dikes are important structurally, because some of the mineralized shear zones developed along their borders.

*The granite and aplitic dikes* are later than the volcanics and earlier than the late diabase dikes. The aplitic dikes are probably related to the granite.

*The late basic dikes* are composed of fresh, homogeneous, black, fine- to medium-grained diabase. They cut across all other rocks in the district and would be considered the last geological event but for the fact that they are displaced by later, north-south trend-

[1] Jolliffe, A. W.: Yellowknife Bay–Prosperous Lake area, Northwest Territories. Canada Geol. Surv. Pap. 38–21, 1938.

ing faults. They vary in width from inches to 450 feet. They dip nearly vertically and most of them were emplaced in tension fractures that had an average trend at right angles to the north-south fault system. Some were introduced along fractures, or faults, trending northward.

*Age of Mineralization.*—There are three possible mineralization epochs that the Yellowknife gold veins may be related.

1. As the gold deposits are found in the youngest, sedimentary pre-Cambrian rocks of the district, they may have been formed during the late pre-Cambrian orogenies in which the younger sedimentary rocks were folded and changed to nodular schists and pseudo-granites.

2. A giant quartz vein, 185 miles northwest of Yellowknife, containing pitchblende, has been dated by its lead-uranium ratio as late Ordovician.[2] It is possible that the quartz veins of Yellowknife were formed at the same time.

3. The Franklin mountains, 140 miles west of Yellowknife, were built during the Laramide revolution. It is possible that the Yellowknife deposits were formed during this orogeny.

## STRUCTURAL GEOLOGY.

*Yellowknife Fault System* (Fig. 2).—The rocks of Yellowknife valley show a maze of north-trending vertical faults. One 450-foot, late diabase dike, already mentioned, crosses the valley and has a total horizontal offset of 11 miles, implying that the Yellowknife fault zone is a structural feature of the first order. In each individual fault, the west side has moved relatively south. The amount of vertical displacement is not known, but, because the rocks on the west side of the valley are older than those on the east side, it is reasonable to assume that, if any did take place, the west side moved up; the east side down. The West Bay fault, the largest of these, has a recognizable horizontal displacement of 5 miles, and trends east of north. It passes through Yellowknife Bay, just skimming the west shore of the Con and Negus properties.

[2] Jolliffe, F.: Yellowknife River Area, Northwest Territories. Canada Geol. Surv. Pap. 36–5: 7, 1936.

*The Shear Zones and Ore Bodies.*—The ore bodies consist of mineralized quartz-carbonate veins that follow well-defined zones of shearing. The width of the zones varies from less than one foot to as much as 18 feet. By surface trenching they have been traced for over 1,000 feet. Their strike, especially those on the west side of the properties, approximates the trend of the nearby West Bay fault. They commonly branch and join (Fig. 3). Dips are to the west and range between 60° and 80°. The shear zones were probably formed by the same stresses that produced the West Bay fault. The material within the shear zones consists of chlorite schist, hydrothermal alteration products of the schist, and veins consisting of an intimate mixture of quartz and carbonate containing metallic minerals. Much of the quartz is dark-gray or black in color, and thin sections show it to contain minute inclusions of chlorite, sericite, and actinolite in contrast to the light colored quartz which does not have these inclusions. Dark colored areas gradually grade into light colored areas in some places, and in others, the boundary between the two is sharp. This suggests that the veins were deposited partly by replacement of the chlorite schist breccia. Drusy joints, vugs, and comb-quartz, however, are very common, so that a considerable amount of the vein matter is fissure filling.

## MINERALOGY.

### *General Statement.*

The mineralogy of the Negus and Con mines is very complex. This complexity is due to four factors: first, the large variety of minerals; second, the presence of rare species; third, the sparse dissemination; and fourth, the exceedingly fine texture. The first impression one receives on preliminary field examination is that there is almost a total lack of metallic minerals in the veins. Pyrite, the most abundant and widely distributed mineral, is not generally visible without a hand lens. The soft, gray metallic minerals are not common. They occur in occasional nests within which they are finely scattered throughout the quartz.

The following mineral descriptions are based on a microscopic study of 60 polished sections mounted in bakelite and polished at

the Mines Branch laboratories, Ottawa. Identifications are based on physical and optical properties, etching behavior, and qualitative analyses, which were performed by microchemical methods, and, in a few cases, by spectrographic methods. The sections do not give a true quantitative picture as they were purposely collected in parts of the mines where gray metallic minerals were most abundant.

The pages to follow merely represent a beginning in the study of the mineralization, for it seems to the writer that practically every polished section examined added another mineral to the list of species already recorded. In other words, if the number of sections studied had been doubled, the list of minerals would probably be increased substantially.

Thirty-three metallic species were identified. Several others were classed as unknowns and have been omitted from this report. Of those identified, only a few are of economic importance; the remainder are mineralogical curiosities. The former group contains gold, tennantite, chalcopyrite, pyrite, arsenopyrite, sphalerite, gudmundite, nagyagite, sylvanite, chalcostibite, and some lead sulpho-salts; the latter group contains galena, altaite, rickardite, siderite, tantalite, and most of the lead sulpho-salts.

### *The Less Complex Minerals.*

*Pyrite* (Figs. 4, 6, 12) is the most abundant metallic and most widely distributed mineral in the ores. It occurs in wall rock and vein material. Polished sections show it to occur most commonly in dark, ribbon-like, partially replaced sericite, calcite, and chlorite areas in quartz. Cubes and pyritohedrons are common forms. This variety of pyrite is commonly fractured and veined by quartz. Pyrite is also plentiful in quartz veins where it exhibits mutual boundaries and crystal faces against quartz; here, it is associated with other metallic minerals. A third mode of occurrence is with vuggy quartz, in colloform structure, and, along with arsenopyrite, was deposited on euhedral quartz grains (Fig. 4).

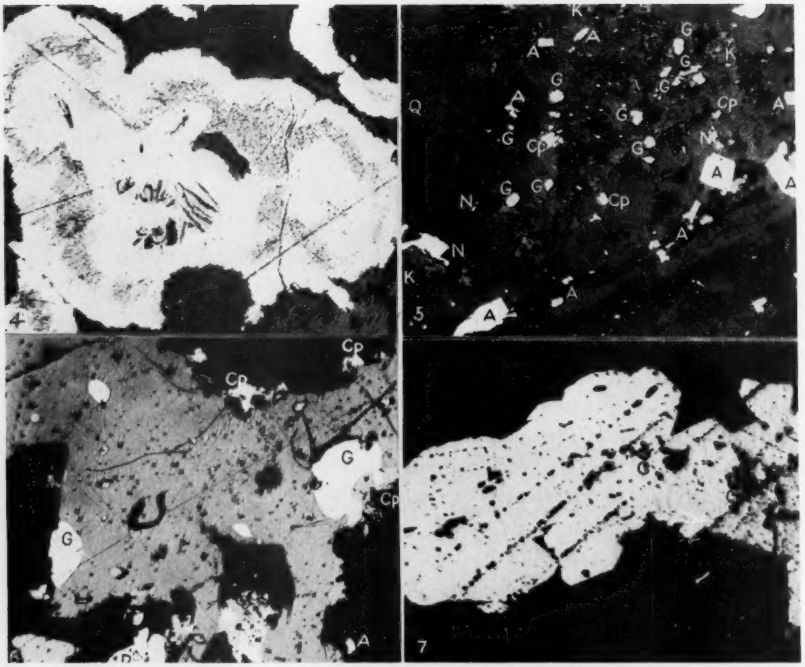



FIG. 4. Colloform pyrite (white) in ankerite (pitted gray). Ankerite partly replaces pyrite. In top right, pyrite is deposited on a quartz grain (gray). × 30.

FIG. 5. Typical disseminated ore. Quartz (Q) is botryoidal under high magnification. Black, gangue inclusions in quartz and ankerite (K). Arsenopyrite (A), nagyagite (N), gold (G), chalcopyrite (Cp). × 50.

FIG. 6. Gold (G) in tennantite (gray). Chalcopyrite (Cp) in large gold area, bordering tennanite, and in gangue (black). × 50.

FIG. 7. Gudmundite (white) corroded by quartz (black) and containing irregular areas of gold (in pits above G). × 50.

*Arsenopyrite* (Figs. 5, 8, 13, 14, 15) is almost as plentiful as pyrite, and it is distributed just as widely. It occurs as small crystals in quartz, commonly clustered in bands, without structural control. It is seldom fractured and veined by quartz. In sections from Zones EF to XZ, arsenopyrite is fractured and granulated, showing that there was post arsenopyrite mineralization movement. Each grain is a single crystal. Irregular inclusions of arsenopyrite are nearly always present in tennantite. In a specimen from Zone KL, an inclusion of arsenopyrite in tennantite contains an inclusion of gold. Arsenopyrite is veined by sphalerite and ankerite.

*Zinc Blende* (Figs. 11, 16).—Microchemical tests indicate that this mineral may be mostly marmatite. It is next in abundance to pyrite and arsenopyrite and was identified in samples from all of the veins.

Zinc blende is associated with practically every mineral in the Yellowknife ores, and its relationships with these other minerals is of great assistance in determining the sequence of deposition. It occurs in cracks in pyrite, arsenopyrite and gudmundite. With quartz its boundaries are very irregular but smooth. Chalcopyrite is commonly found as exsolution blebs in zinc blende. Gold occurs in it as round and ovoid blebs and, conversely, it occurs in gold in round and ovoid blebs. Gold is also found against straight crystal faces of marmatite (Fig. 16). Some marmatite-tennantite contacts are smooth and give no inkling of sequence. On the tennantite side of such boundaries there are irregular inclusions of marmatite, while there are no tennantite inclusions on the opposite side. Zinc blende cleavage controls, to some extent, replacement by galena, boulangerite, chalcostibite, and nagyagite.

*Chalcopyrite* (Figs. 5, 6, 13) was recognized in nearly every polished section. In quantity and texture it differs greatly from pyrite, arsenopyrite, and sphalerite. It is not visible in hand specimens. The two general modes of occurrence are as exsolution specks in zinc blende and as isolated grains in quartz, or rarely, in other minerals. A section from Zone 6 of the Negus shows chalcopyrite veining and replacing tennantite, and in places chalcopyrite contains abundant free gold. A noticeable feature

is that where blebs of gold are disseminated in quartz, chalcopyrite is also distributed as similar isolated blebs.

*Gold* (Figs. 5, 6, 7, 8, 9, 16) is visible to the naked eye in nearly every zone on the two properties. It is very finely divided in both the dark, mottled quartz, and the light colored, fissure-filled variety. Jolliffe[3] describes its field relations as follows:

> In general, gold values are restricted to the veins and the adjoining schist carries only a negligible amount. The gold content of a vein varies greatly within short distances. Thus, one channel sample may contain more than an ounce of gold to the ton and another from the same vein a few feet away only a trace of gold. Available information suggests that as a general rule a high gold content is accompanied by a high content of relatively pure quartz, but exceptions to this occur.

The microscope shows gold in quartz. It was not seen in the carbonate minerals of the veins. It is most abundant in quartz and has various modes of occurrence. In a section from the Negus Zone 6, gold and tennanite together follow short, discontinuous cracks in quartz. In another section from the same locality, the shape of a coarse gold particle is modified by crystal boundaries of quartz (Fig. 16). But on the whole, gold is finely divided in quartz and distributed without regard to grain size, fractures, or grain boundaries.

Of the metallic minerals, gold is most commonly associated with tennantite. Areas measuring between .005 mm. and .2 mm. across occur in tennantite (Fig. 6) with smooth boundaries. There are no fractures or other indications of structural control offered by tennantite for the emplacement of gold. In zinc blende, gold is sometimes seen as blebs. In gudmundite and arsenopyrite, it occurs as irregular shaped areas (Fig. 7). Gold and boulangerite-guitermanite occur with smooth curving contacts. In a polished section from Zone KL, jamesonite projects into gold in one place, and in another gold boundaries appear to be controlled by jamesonite cleavage (Fig. 9). Other contacts are smooth. In a few sections gold and chalcopyrite were seen in irregular contact with one another. Gold and nagyagite may occur separately in quartz (Fig. 5), or within a single quartz grain and in one place nagyagite slightly penetrates a gold grain.

[3] Jolliffe, A. W.: *op. cit.*, p. 22.

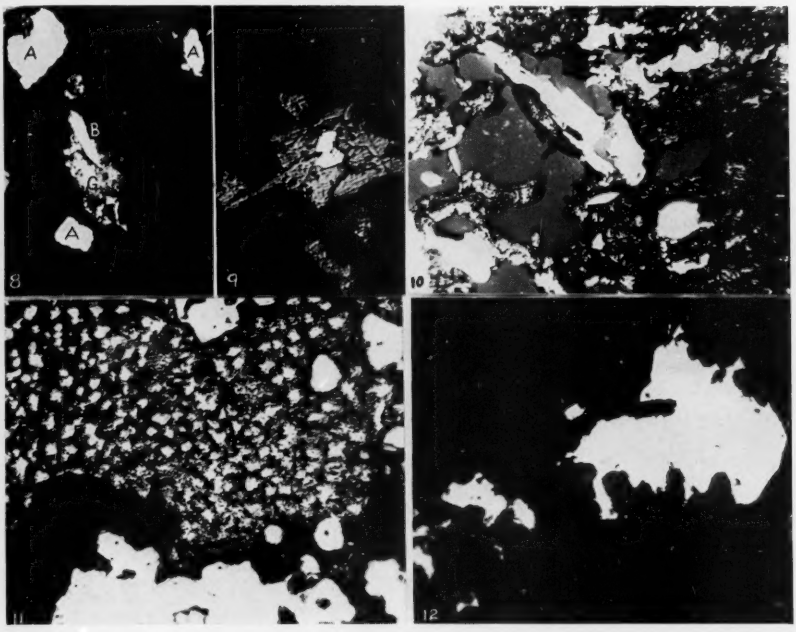



FIG. 8. Gold (G) penetrated by prismatic crystal of boulangerite (B). Arsenopyrite crystals (A) in quartz (black). × 340.

FIG. 9. Gold (white) in jamesonite (gray) with one border parallel to jamesonite cleavage, suggesting that the gold was controlled by jamesonite cleavage, and hence, later than jamesonite. Black is quartz. × 60.

FIG. 10. An area partly covered by drop of KOH showing lengenbachite (white) in stibnite (black) and quartz (gray). Outside the drop, quartz is still gray; lengenbachite and stibnite are both white and indistinguishable from one another. × 55.

FIG. 11. Area etched with dilute $HNO_3$. Small grains of altaite (white) in galena (dark gray, pitted). Large white areas, zinc blende; the large black areas, quartz. × 250.

FIG. 12. Pyrite (white) replaced around borders by hematite (gray). Mottled appearance of hematite is due to internal reflection. × 470.

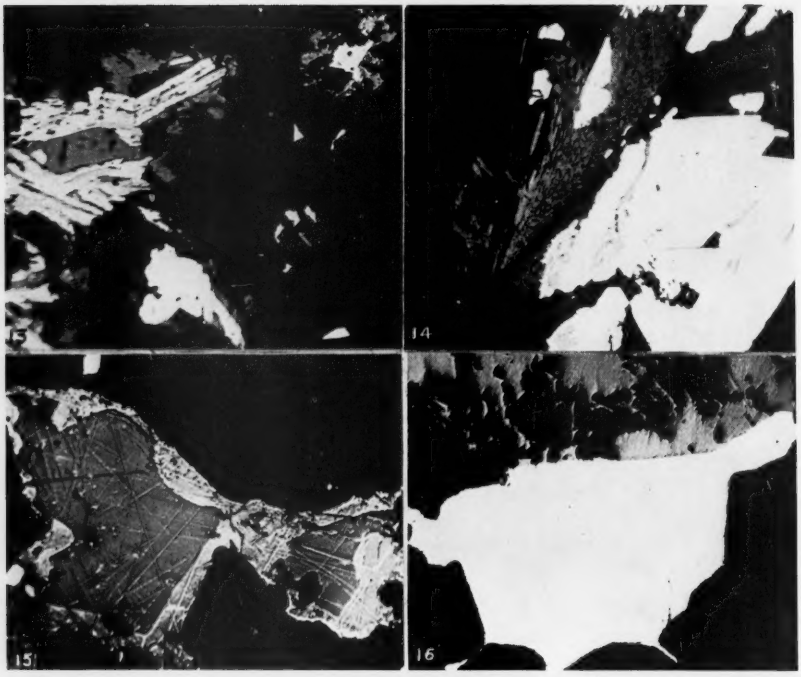



FIG. 13. Upper right, chalcopyrite (white) and nagyagite (gray) with smooth boundaries. Left, dendrites of leucopyrite (white) with nagyagite (gray). At bottom center, arsenopyrite (solid white), leucopyrite (white, dendritic), and nagyagite (gray). × 200.

FIG. 14. Arsenopyrite (white) veined and replaced by acicular actinolite (gray). The large grain near center contains distinct veins of actinolite. Quartz is black. × 200.

FIG. 15. Tennantite (gray) bounded by nagyagite (light gray). Arsenopyrite (white) out in quartz. × 205.

FIG. 16. Gold (white) against a crystal face of marmatite (gray and pitted), and moulded into cusps around crystal grains of quartz (black). The gold projections do not follow fractures in quartz. × 80.

One rich ore shoot encountered in Zone EF, 250 feet below the surface, is reported to run as high as 5 ounces in gold without any of the gold being visible. Polished sections from this zone showed the ore to consist of quartz, considerable pyrite, a little arsenopyrite and veins of a carbonate mineral. On examination with a high power oil immersion objective, ovoid globs of gold less than .005 mm. in diameter were found in pyrite. Although pyrite in places exhibits well defined parting seams and fractures, no gold was seen associated with them.

*Gudmundite* (*FeSbS*) (Fig. 7).—The identity of this rare mineral is based on megascopic and microchemical tests. It[4] is reported from Gudmundstrop, 3 kilometers north of Sala, Sweden, as occurring in a calcite vein associated with lead and zinc ores.

Its microscopic characters are:

COLOR: White, like arsenopyrite, or slightly creamier.
CRYSTALOGRAPHY: Most grains are irregularly bounded, but a few, idiomorphic ones are diamond shaped.
CLEAVAGE: Distinct.
HARDNESS: Very hard, F.
REFLECTIVITY: Brilliant white.
REFLECTION PLEOCHROISM: Nil.
CROSSED NICHOLS: Strongly anisotropic. Two extinctions per revolution. Polarization colors white, gray, green, blue, black, purple, pink, brown —vivid. Reveals structure of fine mosaic of interlocking and interfingering crystals. Twinning common.
ETCH TESTS:
$HNO_3$—slow in starting, stains gray, then iridescent, then black with effervescence.
HCl, KCN, $FeCl_3$, KOH, and $HgCl_2$—negative.
MICROCHEMICAL ANALYSIS:

| | No. 1. | No. 2. | No. 3. |
|---|---|---|---|
| Fe | Strong | Strong | Strong |
| Sb | Strong | Strong | Strong |
| As | Doubtful | Very weak, doubtful | Negative |
| Ni | Indication (not confirmed) | Negative | Negative |
| Co | Negative | Negative | Negative |

The reaction of this mineral to polarized light, and the absence of As in microchemical tests are most diagnostic of the tests.

[4] Johansson, K.: Gudmundit, ein neues Mineral innerhalb der Markasitgruppe. Zeit. fur Krist., 68: 87–92, 1928.

Gudmundite is generously distributed as disseminated aggregates in an almost-black, glassy quartz in specimens from the surface of the southeast end of Zone 10. It is doubtfully recorded in a section from Zone EF. The average size of each individual gudmundite area is .5 mm., and each aggregate is composed of irregularly bounded grains. Boundaries with quartz are quite jagged, but many crystal faces are preserved. It contains minute grains of gold and two or three unidentified minerals; one is possibly boulangerite, another possibly pyrrhotite. Zinc blende veins gudmundite. In the section from Zone EF, small inclusions in chalcostibite and tennatite-tetrahedrite may be gudmundite grains, for their polarization colors seem too bright to be those of arsenopyrite.

*Stibnite* (Fig. 10) was seen only in three specimens from Zone EF, one specimen from Zone UV and one from the small vein southeast of Zone YZ. A hand specimen taken from a 3-inch band of stibnite shows an unusually high concentration of sulphide mineralization for this camp. Microscopically it is not solid stibnite (Fig. 10). Twenty per cent is a cherty quartz, sixty-five per cent is stibnite and fifteen per cent is lengenbachite ($6\,PbS.(Ag, Cu)_2S.As_2S_3$) which is intimately intergrown with stibnite. The stibnite is a fine aggregate of crystals .4 mm. in size. Pyrite and chalcopyrite inclusions are seen frequently in stibnite areas.

*Galena* (Fig. 11) is not of common occurrence. It was found only in Zones 9 and 10 of the Con. Closely associated with galena are boulangerite, jordanite, altaite, and zinc blende, the first two occurring with mutual contacts around borders of galena. Altaite is in the form of numerous, small, four-sided or irregular areas in galena (Fig. 11). Zinc blende is replaced by galena.

*Pyrrhotite* is of rare occurrence. It was found with pyrite, arsenopyrite, leucopyrite, cobaltite, and calaverite in quartz stringers in the hanging wall of Zone 1. It is disseminated in isolated grains in quartz along with chalcopyrite and nagyagite 50 feet below the surface in Zone YZ. It has been recorded as occurring in trenches in Zone CD.

*Hematite* (Fig. 12) veins and replaces pyrite only, in sections from Zone 4 containing pyrite, arsenopyrite, quartz, and carbonate.

*Tantalite* ($Fe(Ta, Mn)_2O_6$).—A pyrite grain less than a tenth of a millimeter in size in a specimen from Zone 9 contains a euhedral crystal that has been tested optically and by etch reagents, which resulted in eliminating all possibilities with the exception of tantalite. This mineral is mentioned here because pyrite commonly contains exceedingly small, unidentifiable grains that seem identical to the one above. It may also have a significant bearing on the presence of tin in the Yellowknife ores. Jolliffe reports tin assays to run from traces to as high as 0.13 per cent. The only other indication of a tin bearing mineral is tennantite.

*Leucopyrite* ($Fe_3As_4$) (Fig. 13) occurs in Zones 1 and 10 associated with cobaltite, calaverite, nagyagite, zinc blende, and pyrrhotite. It exists mostly as small, gently curving prisms, and in places as dendrites in quartz. Its identification is based on the presence of iron and arsenic and the absence of a sulphur indication in microchemical tests, and its reaction to $HNO_3$ in etching tests.

*Cobaltite* ($CoAsS$).—A small area of a polished surface from Zone 1 contains three minerals. Two of these are intimately mixed, and the third veins the mixture. The area was tested with etch reagents and then removed for microchemical analysis with the following results:

| | |
|---|---|
| As | Strong |
| Co | Weak |
| Te | Weak |
| S | Indicated in residue |
| Sb | Nil |

The etch tests indicate calaverite as the veining mineral and cobaltite and leucopyrite as the mixed minerals.

### *The Sulpho-Salts*

*Tennantite-Tetrahedrite* (Fig. 6).—Microchemical and spectrographic analyses of this mineral from different localities show some possible variations in its composition. Every analysis gave a strong arsenic test, and in all but two cases antimony registered

a trace or negative. This implies that the mineral is mostly true tennantite. A sample from Zone 10 and one from Zone EF gave antimony equally as strong as arsenic. Other varieties include a silver-bearing tennantite, a lead-bearing tennantite, and a silver-gold bearing tennantite. A spectrographic analysis of one tennantite gave a trace of tin. The mineral is fairly well distributed, but was not recorded as occurring in Zone 4 of the Con or in any of the Negus Zones with the exception of Zone 6.

*Chalcostibite* ($Cu_2S.Sb_2S_3$) replaces tennantite-tetrahedrite and zinc blende in Zone EF and replaces tennantite in Zone VU. In addition to copper and antimony, a fair test for arsenic was obtained from a microchemical sample of chalcostibite.

*Boulangerite* ($5PbS.2Sb_2S_3$), *Jordanite* ($4PbS.As_2S_3$), *Guitermanite* ($3PbS.As_2S_3$), *Boulangerite-Guitermanite* ($xPbS.y(Sb, As)_2S_3(?)$), *Lengenbachite* ($6PbS.(Ag, Cu)_2S.2As_2S_3$), *Jamesonite* ($4PbS.FeS.3Sb_2S_3$), *and a Bluish-gray Unknown.*—A complex group of antimony- and arsenic-lead sulpho-salts is of common occurrence on the Yellowknife properties. After making a careful study of a group of lead-sulphantimonides, Foley[5] came to the conclusion that the only sure method of identification of such minerals was by means of X-ray analyses. If this be true, then the writer cannot be sure of his identifications. Seven distinct species are recognized in the Yellowknife ores, and the names applied to them are based only on Foley's and Short's[6] etch test descriptions. Microchemical and spectrographic analyses, of course, agree with the formulae of these minerals. One variety, having a reaction to etch reagents that corresponds with those of boulangerite and guitermanite, gives tests for lead, arsenic, antimony and sulphur. These tests suggest an isomorphous series between a lead sulphantimonite and a lead sulpharsenite. This mineral, then, is named boulangerite-guitermanite. Another variety, not identified is described as follows:

COLOR: Gray with slight bluish tinge.
HARDNESS: Soft.

[5] Foley, Frank C.: An X-ray and spectrographic study of lead sulphantimonites. Ph.D. Thesis, Princeton University, Dec. 1937.

[6] Short, M. N.: Microscopic determination of the ore minerals. U. S. Geol. Surv. Bull. 825, 1931.

CROSSED NICOLS:
Strong anisotropism colors on rotation, various shades of gray.
ETCH TESTS:
$HNO_3$—Stains gradually through iridescent to black, followed by effervescence.
HCl—Stains brown.
KCN—Negative.
$FeCl_3$—Stains strongly iridescent.
KOH—Stains faintly brown.
$HgCl_2$—Negative.

MICROCHEMICAL ANALYSIS:
Pb—Strong
Sb—Strong
As—Fair
Te—Weak
Bi—Nil

*The Tellurides.*

*Nagyagite* (*Pb, Au, Sb, Te, S*) (Figs. 5, 13) is well distributed in samples from the 106 H stope of Zone 10, the 204 drift north of Zone 4, and the inclined shaft on Zone YZ. It is by far the most predominant telluride. It is disseminated in quartz along with its closest associates, chalcopyrite and gold, and in places it occurs in contact with these minerals. Polysynthetic twinning is common. Microchemical tests confirmed the presence of lead, tellurium, and antimony, but not of gold.

*Sylvanite* ($(Au, Ag)Te_2$), in a sample from Zone YZ, occurs on the borders of a nagyagite grain with automorphic boundaries between them.

*Calaverite* ($(Au, Ag)Te_2$) is recorded only in a section from Zone 1, veining leucopyrite and cobaltite.

*Altaite* (*PbTe*) (Fig. 11) occurs with galena in Zone 9.

*Rickardite* ($Cu_4Te_3$).—A mineral disseminated in quartz and having the optical properties, which are highly characteristic of rickardite, was recorded in a section from Zone YZ. This mineral, however, could not be relocated so its identity was not confirmed.

*The Non-metallic Minerals.*

*The country rock* is not noticeably altered in the vicinity of the veins. In places it is bleached from the usual dark green to a yellowish gray color. The original andesites were regionally al-

tered, probably long before the introduction of the veins, to a fine-grained, soft, chloritic rock. Adjacent to the quartz-carbonate veins the country rock is composed of quartz, sericite, calcite, actinolite, chlorite, and pyrite.

*Quartz* is the predominating gangue mineral. It is quite heterogeneous in general appearance, but in texture it is more uniform. It varies from black through various shades of gray, to white. The white variety is considered to be fissure filled, the black to be replacement of the breccia in the zones. Gold occurs in both types, and stands out impressively against the dark translucent background of the replacement type. Thin sections show this quartz to contain minute inclusions of sericite, chlorite and actinolite, which presumably accounts for its dark color. Its texture is very fine grained. In hand specimens it commonly exhibits a cherty or glassy appearance. It commonly shows comb structure. Extinction is sometimes mottled and nearly always undulatory. The quartz is of more than a single age because little veinlets may be seen intersecting the other quartz areas.

*Calcite* is a constituent of the wall rock and is also common in the partially replaced areas of the quartz veins where it is associated with chlorite, sericite, actinolite, and pyrite.

*Siderite* occurs in some of the veins, particularly CD, where lenses of it are 3 or 4 inches wide. It is also disseminated in quartz as small grains, or little discontinuous veinlets. Quartz of a later age cuts across siderite areas.

*Ankerite.*—The bulk of the vein matter is made up of quartz and a grayish-white carbonate consisting of ankerite and possibly small amounts of calcite. The carbonate is commonly drusy, and fine-grained, but coarser than quartz. It replaces and fills fractures in quartz and other vein minerals freely. A great deal of it is also fissure filling. No metallic minerals are associated with it.

*Actinolite* (Fig. 14), as well as being a main constituent of the wall rock, is present throughout the dark quartz. In polished sections it is gray, resembling the color of sphalerite, hard, negative to all reagents, and has white internal reflection. It may be seen as acicular crystals that diverge from a point and penetrate crystals of arsenopyrite and pyrite (Fig. 14). It has the appearance of

a vein mineral, but its presence might be explained as having its origin in the country rock, and becoming included in the vein matter as the mineralizing solutions dissolved the surrounding chlorite, sericite, and calcite more easily.

### *The Supergene Minerals.*

Supergene mineralization is not important at Yellowknife. Specimens collected from trenches, which have been excavated to depths of 10 feet, show a considerable amount of secondary minerals. On the other hand, specimens collected underground from shafts and raises not 30 feet below the surface, show no secondary alteration. This points to the conclusion that the limit of downward enrichment lies between 10 and 30 feet below the surface.

*Covellite, chalcocite, malachite, limonite and other oxides* are common supergene minerals that vein tennantite, chalcopyrite, sphalerite, and other primary minerals.

*Gold.*—In two sections from surface trenches gold is associated with secondary minerals. In one, gold grains were seen in the center of a limonite vein in tennantite. In the other, gold occurs in chalcopyrite with a peculiar, layered, concentric structure separated from the chalcopyrite on all sides by limonite. The concentric form of the gold suggests colloidal deposition. The limonite entered the chalcopyrite grain by means of a crack which is visible in the section. Whether or not the gold entered the chalcopyrite by the same crack is not known. It is quite possible that the gold was there in the first place and the limonite just preferred to make its way along the gold-chalcopyrite boundary.

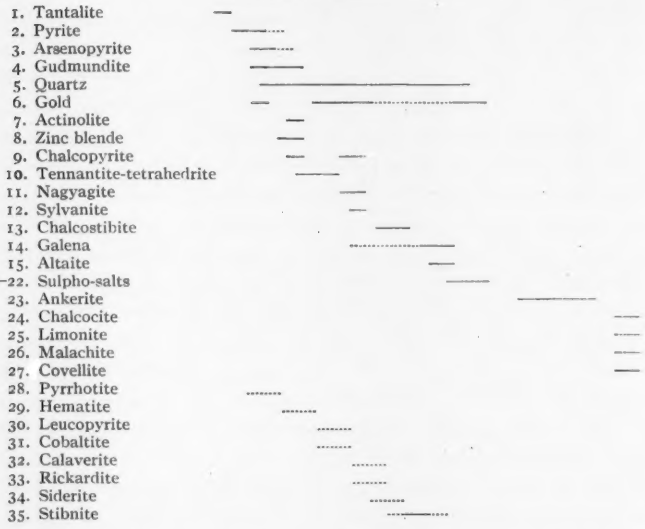
### *Paragenesis.*

*The Table.*—The minerals are listed in Table I beginning with the earliest. Due to the isolated distribution of some, it has been difficult to determine their relation with the others. Hence, the doubtful ones are placed at the bottom of the column and dotted lines represent proposed periods of deposition.

*Discussion.*—The paragenetic sequence may be divided into a hydrothermal and a supergene stage. The supergene stage does not exist 30 feet below the surface and is relatively unimportant.

TABLE I.

MINERAL SEQUENCE.




The hydrothermal stage may be divided into two substages. The first has quartz as its predominant gangue mineral and all the metallic minerals were introduced during this substage. In the second substage, ankerite and small quantities of other carbonates were deposited.

In the first, tantalite, pyrite, arsenopyrite and gudmundite were the first minerals to crystallize. The first three are commonly euhedral and pyrite may be seen replacing tantalite, and arsenopyrite replacing pyrite. Actinolite veins pyrite and arsenopyrite, but is also seen in mutual relations with these minerals. Quartz boundaries with pyrite, arsenopyrite and gudmundite show that it was deposited partly simultaneously with them and partly later, for these sulphides have crystal faces in places, yet are commonly corroded and replaced by quartz. Zinc blende veins pyrite, arsenopyrite and gudmundite; and has smooth, mutual contacts with quartz, gudmundite and tennantite-tetrahedrite. It more com-

monly occurs in tennantite-tetrahedrite as replacement remnants so that the latter mineral is shown as having overlapped zinc blende a little, and having continued beyond. Most of the chalcopyrite followed tennantite-tetrahedrite, for it is deposited on borders of the sulpho-salt and sometimes veins it. Some chalcopyrite accompanied the formation of sphalerite as exsolution blebs. Chalcopyrite and nagyagite have automorphic contacts. Sylvanite occurs in border regions of nagyagite areas. Chalcostibite replaces tennantite-tetrahedrite at borders and contains chalcopyrite inclusions. Galena is later than sphalerite, but just when it began to form, with respect to the other minerals, is not known. Jordanite occurs with galena in much the same manner as sylvanite does with nagyagite. Altaite occurs as irregular and rhombic-shaped, equal-sized areas in galena, suggesting contemporaneous deposition. Boulangerite, jordanite, boulangerite-guitermanite, lengenbachite, and jamesonite replace all other hydrothermal stage minerals with the exception of ankerite.

*Gold.*—A long period of deposition for gold is indicated by the variety of relationships it has with its associates. It occurs as minute blebs in some homogeneous pyrite, sphalerite, and quartz (Fig. 5). Gold, finely divided in this manner, is distributed without regard to grain size, fractures, or grain boundaries and, hence, is believed to have been deposited simultaneously with these minerals. In tennantite and other sulpho-salts it occurs as blebs and larger areas with automorphic contacts. Gold, in one place, appears to have been deposited on nagyagite, and, in another, the telluride partly penetrates the border of a gold particle.

Similarly, with the sulpho-salts, gold shows relations that suggest earlier deposition in some places and later deposition in others. Boulangerite (Fig. 8) penetrates an area of gold, indicating earlier gold; and jamesonite (Fig. 9) contains a particle of gold in which there is a suggestion of cleavage control on the part of jamesonite, indicating later gold. On the whole, however, gold and the sulpho-salts show contemporary relationships.

Not only is gold in quartz as automorphic inclusions, but it may be seen moulded around and between crystal boundaries of

quartz. Fig. 16 shows a crystal face of zinc blende on which gold and quartz were deposited. The gold partially penetrates areas between quartz crystals. For two reasons the gold is believed to be contemporaneous with quartz. First, there are no fractures in the gangue mineral to guide the prongs of gold. Second, the hand specimen, from which the polished section was taken, consists of white, comb quartz of the fissure filling variety, with disseminated specks of visible gold and gray metallic minerals. The fissure was not completely filled, and one side of the specimen was part of the wall of a vug. Gold and metallics are heavily concentrated together in the first one-quarter inch of quartz in from the vug wall. Beyond this, gold is not seen and the metallics gradually fade towards the wall of the fissure. This is interpreted to mean that the earliest quartz to be deposited by solutions passing through the fissure was (visibly) barren. Then, as the closing stages of filling approached, the gray metallics were deposited in increasing amounts; and, in the final ¼ inch of filling, gold accompanied the deposition of tennantite, zinc blende and quartz. Hence, in the area photographed, gold and quartz crystallized together, and, because of the superior crystallizing power of quartz, the gold yielded to the quartz crystals and was deformed into cusps that project between crystals.

Zinc blende, tennantite-tetrahedrite, chalcopyrite and gold sometimes may be found as veins in discontinuous fractures in quartz. Their deposition was evidently accomplished by some replacement of predeposited quartz.

Ankerite followed quartz and the metallic minerals. All boundaries between them are highly irregular and show replacement by ankerite. Some sections showed the ankerite substage to be separated from the quartz substage by a period of fracturing; others imply that, because of the intimate association between them, the carbonate closely followed deposition of the quartz.

*Minerals with Uncertain Relations.*—Pyrrhotite is later than pyrite and earlier than chalcopyrite. Hematite replaces pyrite and is disseminated in quartz. Leucopyrite crystallized between pyrrhotite and nagyagite. Cobaltite shows mutual relations with

leucopyrite; calaverite veins leucopyrite; rickardite and siderite were seen only in quartz; and stibnite was deposited some time between chalcopyrite and boulangerite.

*Fractures.*—First generation pyrite and arsenopyrite crystals are not oriented to the foliation of the schist, inferring that they were produced later than the formation of the schist breccia within the zones. The first part of the hydrothermal stage was followed in most zones by a period of fracturing, for nearly all the early pyrite and some of the early arsenopyrite were fractured and veined by later quartz, carbonate and metallic minerals. Then, in the second part of the hydrothermal stage, there is evidence of more than one generation of fracturing, for younger quartz stringers intrude earlier vein quartz. The metals were introduced with more than one age of quartz. Gudmundite, pyrite, and arsenopyrite may have been confined to earlier quartz injections, and sulpho-salts to later ones. Gold, zinc blende, and tellurides accompanied both. Another strong fracturing epoch occurred between the quartz and ankerite substages.

## CHARACTER OF ORE-BEARING SOLUTIONS.

*Composition.*—The metals occurring in the veins could be explained as having been transported in the form of electrolytes or true solutes in aqueous solutions. Still, there are factors that suggest colloidal agencies also played a part. Colloform pyrite, for instance, and the extremely fine-grained quartz that, in a hand specimen, has a distinct cherty appearance. The long range deposition of the gold, too, implies colloidal transportation, because, if the gold had been carried entirely in true solution, it would be expected to have a short, single place in the paragenetic sequence.

In the light of Frondel's [7] experiments with colloidal gold solutions, the following account is offered to explain the origin of the deposits.

The ore-bearing solutions were composed of Ta, Mn, Fe, As, Sb, Zn, Ca, Cu, Te, Au, Ag, Pb, S, Si, and $H_2O$. The metals

[7] Frondel, Clifford: Stability of colloidal gold under hydrothermal conditions. ECON. GEOL., 33: 1–20, 1938.

were transported in various electrolytic forms or in true solution. Successive stages of movement in the zones permitted passage of the hot, aqueous solutions, which readily attacked and dissolved the ferromagnesian schist breccia. As the pH dropped, the metals began to precipitate, beginning with tantalite, and followed by pyrite, arsenopyrite, gudmundite, quartz and the other hydrothermal minerals. Gold and silica were discharged as solutes, but retained as dispersed colloids, while the solutions became neutral and alkaline.

In discussing the method by which gold may be removed from dispersion, Frondel states:

> Gold may . . . be removed from dispersion by the direct adsorption of the particles upon crystal surfaces exposed in the solution. If the adsorpting crystals are growing, the gold particles will be buried as finely divided inclusions. The adsorption may be selective between minerals of different species. Gel surfaces may similarly remove colloidal gold from dispersion.

This adequately explains the occurrence of gold in pyrite, sphalerite, tennantite (Fig. 6), and quartz (Fig. 5). Regarding selective adsorption, tennantite is the outstanding species.

*Temperature.*—Low-temperature and high-temperature minerals have not yet been recorded. Hence the solutions may be considered as having been intermediate in temperature. The minerals hematite and pyrrhotite are not, in general, restricted to high temperature veins and are of rare occurrence on the Yellowknife properties.

*Pressure.*—Vugs, crustification, comb structure, and some banding suggests near-surface deposition. This is strongly supported by one of the most characteristic features of the deposits —the extremely fine texture. The deposit, therefore, is classified as mesothermal, although it possesses certain epithermal charactristics.

## CONCLUSIONS.

At the time of writing, drill results have indicated ore values to a depth of 1,000 feet, and underground workings have only reached a depth of 400 feet. It is difficult, therefore, to estimate the importance of the deposits. The following conclusions are admittedly speculative.

1. The Negus and Con deposits may be expected to persist to considerable depth.

2. Gold values may possibly be found to decrease gradually with depth.

There are two reasons for the above two statements.

*A.* The first is based on the mineralogical features of the gold. Cummings and Warren [8] noticed that in British Columbia gold mines, where the gold is intimately associated with a certain sulphide, gold values disappear in depth where the related mineral disappears. At the old Ymir mine, gold is intimately associated with galena. Where galena disappeared in depth, so did the gold. Another example mentioned by them is that of the Pioneer mine. Gold is related only to quartz, and has a proved vertical range of 3,000 feet and the limits have not yet been determined. At the Negus and Con, gold occurs with persistent minerals such as quartz, zinc blende, pyrite and arsenopyrite, and, hence, should have a large vertical range. A great deal of the gold, however, is associated with tennantite, a mineral with a less extensive vertical range of deposition, so that gold values may be found to decrease gradually with depth.

*B.* The second reason is based on the close parallel between the Yellowknife deposits and those of Kalgoorlie, Western Australia. At Kalgoorlie,[9] the ore is found in short, parallel trending, shear zones near acid dikes in schistose greenstones of pre-Cambrian age. The veins consist of quartz and carbonate minerals, and at places the gangue includes albite, roscoelite, fluorite, sericite and chlorite. The most common metallic minerals are pyrite and gold and the following minerals,[10] also present, resemble closely the assemblage at Yellowknife: pyrrhotite (rare) arsenopyrite, tetrahedrite-tennantite, seligmanite in an isomorphous series with bournonite, enargite, jamesonite, stibnite, galena (rare), sphalerite, chalcopyrite, hematite, magnetite, tellurium, altaite, coloradoite,

[8] Warren, H. V., and Cummings, J. M.: Texural relations in gold ores of British Columbia. A. I. M. E. Tech. Pub. No. 777.

[9] Stillwell, F. L.: Geology and ore deposits of the Great Boulder, Kalgoorlie. W. Australia Geol. Surv. Bull. 94: 1–110, 1929.

[10] Stillwell, F. L.: The occurrence of telluride minerals at Kalgoorlie. Proc. Australia I. M. M. No. 84: 115–190, 1931.

melonite, rickardite, tetradymite, hessite, stützite, antamokite, petzite, sylvanite, krennorite, calaverite, and nagyagite. Another similarity between the Yellowknife and Kalgoorlie gold deposits is the general absence of bismuth. A dissimilarity is the abundance and importance of tellurium minerals at Kalgoorlie, for at Yellowknife they are rare.

At a depth of 3,800 feet below the surface, the Kalgoorlie mines were still in ore, but the value of the ore, which, at the surface, averaged between $30 and $40 to the ton, gradually declined to $7 to $10 in the lowest levels.[11]

3. A factor that may limit the depth of the ore is the possibility of a shallow, eastward plunge of the adjacent granite batholith.

4. It might be pointed out that Yellowknife possesses certain geologic features that are characteristic of other mining districts. For instance, the occurrence of late diabase dikes that are possibly genetically related to quartz-carbonate veins compare with those of other gold mining districts mentioned by Spurr.[12] Again, great tear faults, one with a horizontal displacement of 5 miles, compares favorably with those in other parts of the continent discussed by Billingsley and Locke.[13] It seems plausible, therefore, to expect that the Yellowknife field may soon become an important mining district.

PRINCETON UNIVERSITY,
PRINCETON, NEW JERSEY,
*Aug. 1, 1940.*

[11] Lindgren, W.: Mineral Deposits. McGraw-Hill, 1933, p. 680.

[12] Spurr, J. E.: Diaschistic dikes and ore deposits. ECON. GEOL., 34: 41–48, 1939.

[13] Billingsley, P., and Locke, A.: Structure of ore districts in the continental framework. A. I. M. E., 1939.

# THE PERSPECTOGRAPH.

GEORGE W. BAIN.

ABSTRACT.

The perspectograph is a device designed to convert plans of any sort to perspective drawings. Plans for different levels are superimposed by the machine to give accurate controls for a block diagram. Adjustable settings will give the perspective from any angle of elevation or obliquity. Any diagram reproduced by this device is correct to scale.

## INTRODUCTION.

Most structural geologists have had the desire to illustrate their work and to study structures with solid models or, falling short of models, a drawing which would simulate a solid. Unfortunately few possess manual dexterity equal to their mental vision and rarely do they continue their efforts beyond the first perspective diagram. Every case of discouragement can be traced to inadequate physical control over the shaping lines on the completed sketch. The perspectograph was designed specifically to furnish that necessary physical control for those men lacking control and training in principles of perspective.

*General Usefulness of Perspectograph.*—Accurate perspective drawings are more useful to study of a region by the worker than to illustration of its features for the reader. For study purposes drawings should be made to scale so that changes in magnitude of features receive true values. At present most block diagrams are subjective illustrations; however they become objective records when they are made under accurate perspective controls. The latter type of diagrams becomes very useful in general structural and physiographic study of a region. They find another use in study of structure contour maps that use a sea level datum plane; an accurate perspective drawing can be made so that the angle of view is down the regional dip which then becomes equivalent to a datum plane with minor structures as relief fea-

tures on it. The probable visibility from a lookout tower of the forest service may be important; it can be determined with the perspectograph by using the top of the tower as the point of view and reproducing the contours of the topographic maps until no more are visible; the remainder of the country is the portion concealed from view at the lookout station.

*Factors Controlling the Design.*—A machine, to be effective, must respond to very little force at the control or stylus point following the contours of a topographic map. It must be light to reduce inertia. Also friction on moving parts must be low to permit facile response to slight movement. All moving parts must fit accurately to remove free motion.

The transfer of positions from a topographic map drawn on one scale to a perspective diagram on another scale involves resort to a pantograph link system. The pantograph becomes inaccurate if used beyond the limits for which it is designed and therefore the design of the perspectograph is controlled partly by the size of the topographic sheets to be used on it.

The design is so simple and operation so elementary that the novice can use the machine. It was felt that if the apparatus was available to experienced operators only, it would do little to facilitate the work of most structural geologists.

## GENERAL DESIGN.

The problems of design fell under three headings. First was the selection of materials. Second was planning the kinematics of the various links so that the movement of the stylus or tracing point on a plane viewed from above would be transferred to a reproducing point as an oblique view at a definite predetermined angle. The third group of items involves selection of strips, channels, plates and other structural materials of proper size and rigidity.

### *The Materials.*

Light weight ST–17 aluminum alloy was used where possible in order to reduce weight. Stainless steel was substituted at places subject to wear. Pin bearings were used for rolling parts

in preference to ball bearings because they have almost as low friction and move in a more accurate path.

*The Theory of Kinematics of Design.*

The theory of the design follows four principal rules.

1. Lateral or east-west (E.W.) motion of the reproducing point must parallel the stylus or tracing point.
2. This horizontal E.W. motion is shortened in proportion to approach of the horizon.
3. The vertical, north-south (N.S.) motion of the reproducing point must be reduced as it approaches the horizon.
4. The N.S. and E.W. components of movement must be coordinated at the reproducing point.

The map which is being traced by the stylus *A* (Fig. 1) and the paper below the reproducing point *B* are stationary for perspective reproduction at any given datum. The map and the pivot *C* for the convergence control arm are moved up or down an appropriate amount to reproduce higher or lower data.

*The E.W. Motion.*—The E.W. motion of the reproducing point is along parallel E.W. paths controlled by rolling the entire link system *DEFGHI* (Fig. 1) on a track. All E.W. motion of *B* is controlled by the E.W. motion of *C* which is always exactly equal to that of the tracing point *A*. But amount of motion at *B* diminishes as the reproducing point moves from *C* towards *J;* *J* is a fixed point on the horizon line of the diagram. This proportional reduction of movement of *B* relative to *C* accomplishes the E.W. foreshortening.

*The N.S. Motion.*—The N.S. motion is controlled by the arm *AI* and the side link *KL*. The arm *AI* is free to slide at *I;* the link *KL* is hinged at both *K* and *L* and is attached to a carriage *MN* which can move only N.S. on its track. The reproducing point *B* must move N.S. with the carriage *MN* and also E.W. with the arm *CJ*.

The lengths of the link *KL* and of the arm to *AK* are fixed and the position of the point *I* is adjusted at the start of operations so that the motion from *L* to *L''* is equal to the apparent

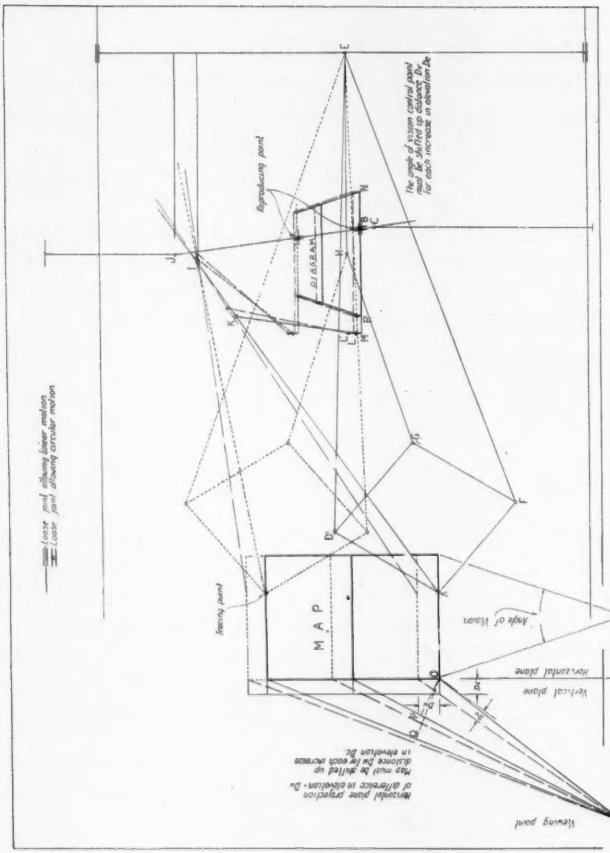



FIG. 1. Diagram showing the theory and motion controls for the perspectograph.

length *OQ* for the map as seen from the viewing point. (In practise the points *I* and *J* are set for different angles of view according to a scale on a sliding arm holding the respective sliding pivot points.)

*The Vertical Component on the Diagram.*—Contours are interval lines and so the vertical component of motion on the perspectograph is arranged for interval settings. The elevation interval *De* appears from the viewing point as a difference *Dv* and the map must be moved northward an amount *Dh* to have the higher levels reproduced in their proper position. However this places the map more distant and diminishes the E.W. movement of *B*. This is corrected by moving the pivot point *C* of *JBC* northward until the E.W. width of the map on the diagram is equal to *RN*.

*General Results of Movements.*—The coordinated E.W. and N.S. movements of the tracing point *A* and the reproducing point *B* convert the forms on the map to the appearance they assume as seen from a viewing point of selected elevation above the map and distance away from it. In Fig. 1 the viewing point is placed directly south of the mid-point; had it been to eastward, the pivot point *J* would have been moved eastward an equivalent amount.

The levels change by increments just as the contours reproduced are distinct intervals. However they are reproduced objectively to scale as truly as the plan of any given level is reproduced.

## *Practical Features of the Design.*

The perspectograph will diagram the three coordinates of a solid. The controls for each of the three coordinates requires its own particular set of specifications. Assembly of the apparatus is shown on a series of diagrams that illustrate the necessary parts at different levels from the table upwards. This particular arrangement of apparatus has been found most satisfactory of all those tried. Rolling bearings have lower friction than sliding elements and have been adopted everywhere. The drawings show the component parts at different levels upwards from the map and diagram table, but significant features of each part are described below according to the motion they control.

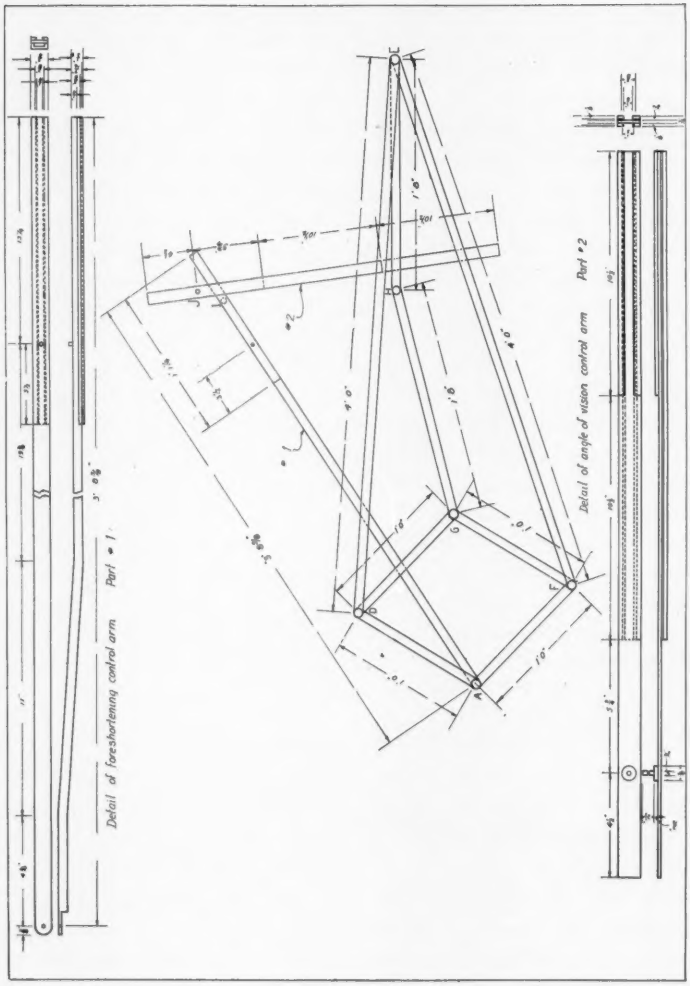



FIG. 2. Details for pantograph used to transmit the stylus motion to the carriages controlling the reproducing point.

*E.W. Motion—Convergence to Horizon.*—Parallel E.W. motion is attained by the main rolling carriage that supports the entire link system; only one point, namely, the pivot *J* for the angle of vision or convergence control arm, is connected to the table bearing the map and the diagram paper. The swings of this arm, as the pivot point *C* moves back and forth with the carriage, causes the reproducing pencil point *B* to trace the lines on the paper. The carriage is moved back and forth by the pantograph link system *ADEFGH* (Fig. 1).

*The Carriage.*—The carriage (Fig. 4) consists of a frame of 1¼ in. × 1¼ in. × ⅛ in. aluminum alloy channel. Corners are bracketed with ⅛ in. aluminum plate to make the assembly rigid. The wheels, supporting the carriage frame, have 2⅞ in. diameter at the bearing surface. Wheels on the south side of the carriage have a "V" groove to insure parallel motion along the track. The ½ in. stainless steel rod at the east side of the carriage is used to make N.S. adjustments of the pantograph for the more complex type of perspective diagrams.

The carriage has two adjustable pivot points with rollers to facilitate sliding motion; also it supports a track for another carriage moving in the N.S. direction. The pivot *C* (Fig. 4) has a roller that fits into the upper or short groove in the E.W. convergence control arm. This pivot is on the end of an adjustable arm so that its distance from the south edge of the carriage may be modified to give contour interval changes on the diagram. The pivot *I* engages in the groove under the long connecting arm (Fig. 2), which is linked to the tracing stylus *A* and also to the carriage controlling N.S. motion of the reproducing point by the strip *KL*. The position of *I* is adjustable for different elevations of the viewing point.

The N.S. carriage has two side arms that move between two pairs of flanged rollers. These rollers are on the cross bars of the main carriage frame and allow the N.S. carriage to move only in a N.S. direction. This carriage is described later.

*The E.W. Convergence Arm Controlling Angle of Vision.*—The E.W. convergence arm is made of aluminum alloy strips

FIG. 2. Details for pantograph used to transmit the stylus motion to the carriages controlling the reproducing point.

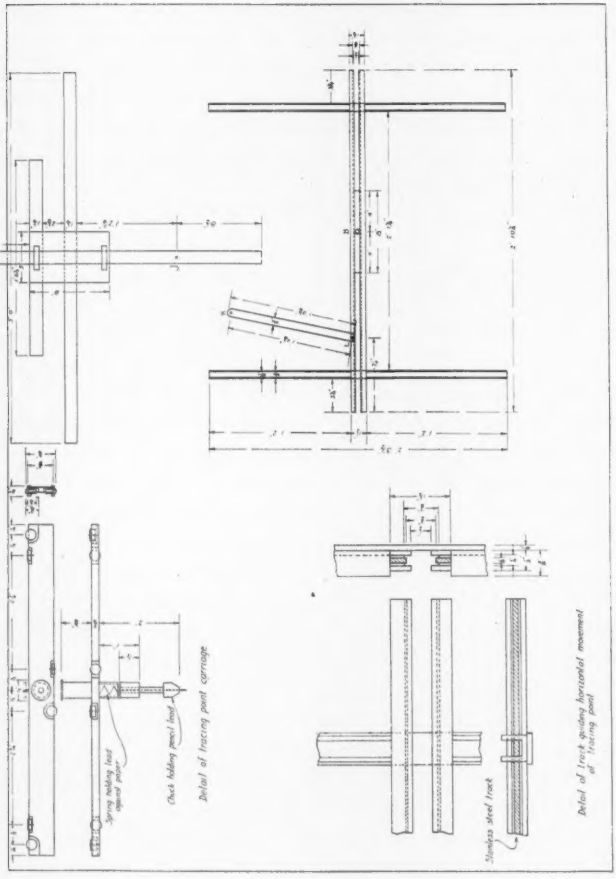



FIG. 3. Details for N.S. carriage and the tracing point carriage.

built up so as to have slots on the under side for the pivot head above the reproducing point (Fig. 3, part 1) and on the upper side for the pivot *C*. The details appear in Fig. 2, part 2.

The E.W. convergence arm is pivoted at the fixed point *J*. This point may be fixed or adjustable depending upon requirements; it must be adjustable if the elevation of the point of view and obliquity of view are to be varied. Consequently, this point is on a piece of 1¼ in. × 1¼ in. × ⅛ in. channel that can be withdrawn or extended in a N.S. direction to vary the height of view; it is held in the desired place by a set screw.

The channel carrying the pivot head rests across an 8 in. × 5 in. aluminum plate screwed to two east-west pieces of 1¼ in. × 1¼ in. × ⅛ in. channel. These slide on an E.W. guide and can be clamped in place; if they are moved eastward they give an oblique view of the region to be represented as it would appear from the east.

*The Foreshortening towards Horizon or N.S. Motion.*—Parallel N.S. motion is obtained by the carriage (Fig. 3) which moves between the four pairs of flanged roller guides on the E.W. or main carriage (Fig. 4). This N.S. carriage is moved back and forth by the connecting link *KL* of ⅛ in. × ¾ in. aluminum alloy. This link is controlled by the sliding arm *AI* shown in detail in Fig. 2, part 1.

*The N.S. Carriage.*—The N.S. carriage has a cross track for the tracing point carriage. This allows free E.W. motion of the tracing point so far as N.S. control is exercised and unlimited N.S. motion so far as the convergence or E.W. control is concerned; however these controls are crossed and for any setting of the tracing stylus the only location for the reproducing point exists at the intersection of the two controlled paths.

The track for the reproducing point is built up of five sections. Four sections are of aluminum alloy and the fifth or cental one is stainless steel. Steel was used for this part to reduce wear caused by frequent back and forth movement of the tracing point carriage.

The two sides of the track are screwed to 1/8 in. × 3/4 in. aluminum alloy strips of the N.S. carriage arms. These strips are stiffened by 5/8 in. × 5/8 in. × 3/32 in. aluminum alloy channel.

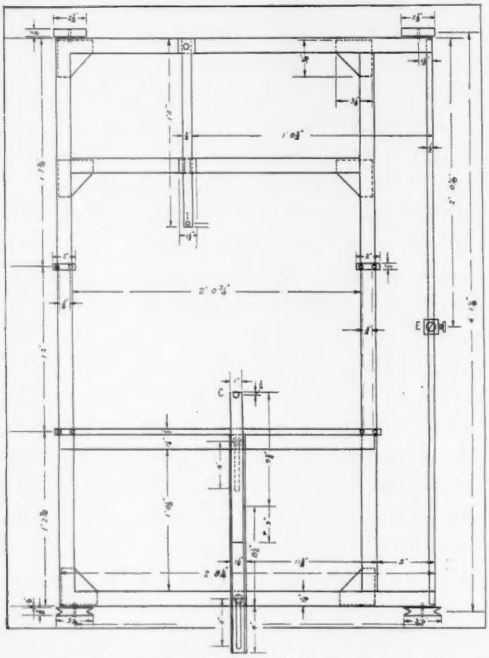


FIG. 4. Details E.W. carriage with pivot points for pantograph control.

*The Reproducing Point Carriage.*—The reproducing point moves with a carriage having a 6½ in. wheelbase (Fig. 3, part 1). This length of base steadies the movement where the rollers fail to make firm contact with the track. This carriage has three horizontal and three vertical rollers. Two of each are on the same side of the carriage but at opposite ends. The third of each roller type is on the opposite side and in the middle of the carriage.

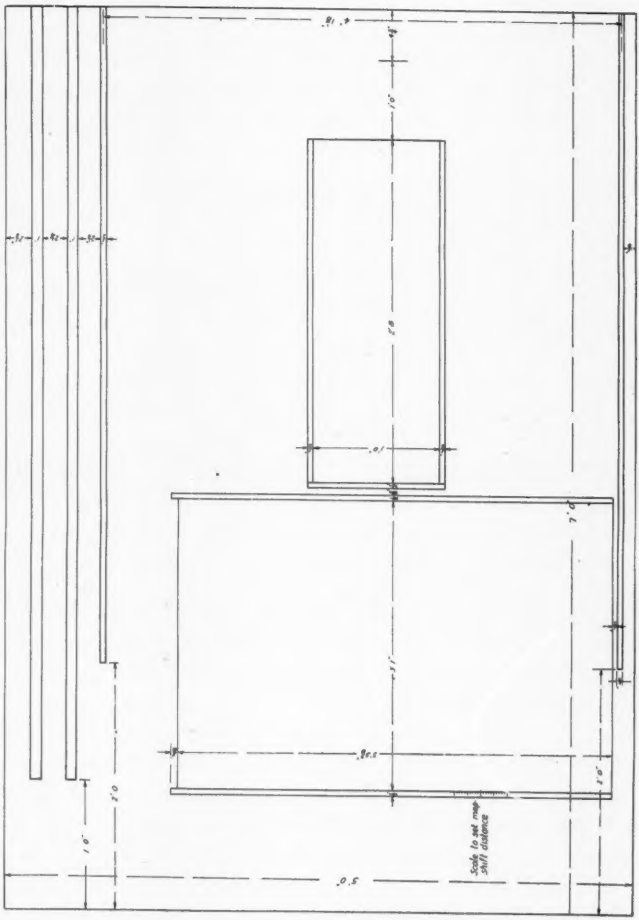



FIG. 5. Diagram table showing location of fixed tracks and guides for apparatus, map and diagram sheet.

The pencil lead of the reproducing point is gripped in a chuck and this is pressed against the recording paper by a light spring below the reproducing pivot.

*The Pantograph Arms.*—The pantograph (Fig. 2) is made of ¾ in. × ⅛ in. aluminum alloy strips. Stiffeners should be placed along the top of these thin strips although they are not absolutely necessary. The pantograph transfers only E.W. motion to the main carriage and makes the transfer in a one to one ratio. Reduction of the E.W. distance with approach to the horizon is obtained by the angle of vision or convergence control arm.

The end of the two long side arms of the pantograph are supported on spindles with rollers in the bottom. This reduces weight on the stylus tracing point.

The stylus tracing point has two pantograph links and a third bar of ⅜ in. × ¾ in. × 3/32 in. channel attached to it. The third bar is the one that controls the N.S. motion.

*The Table* (Fig. 5).—The apparatus is set on a substantial 5 ft. × 7 ft. hardwood table. However if moisture changes are exceptionally great, a metal top is recommended because shrinkage and expansion of the wood causes serious binding in the moving parts.

The north side of the table has two long upright tracks to guide the 1¼ in. × 1¼ in. × ⅛ in. channels that control the obliquity of view. Two ½ in. stainless steel rods 4 ft. 1⅛ in. apart serve as tracks for the E.W. carriage.

Two sets of guides for sheet holders are screwed to the table top. The eastern set holds the diagram sheet and needs no special adjustment. The western set of guides is for the map sheet holder and must have adjustments and a scale for N.S. movement. This is essential to reset the maps in order to reproduce the contour levels on the diagram. The holders for both map and diagram sheet may be made of wood but metal is to be preferred if wood swells or warps in the building where the instrument is to be used.

*Arrangement of Figures to Illustrate Assembly.*

Superposition of the drawings with Fig. 5 at the bottom and Fig. 2 at the top places the parts in proper order from the table

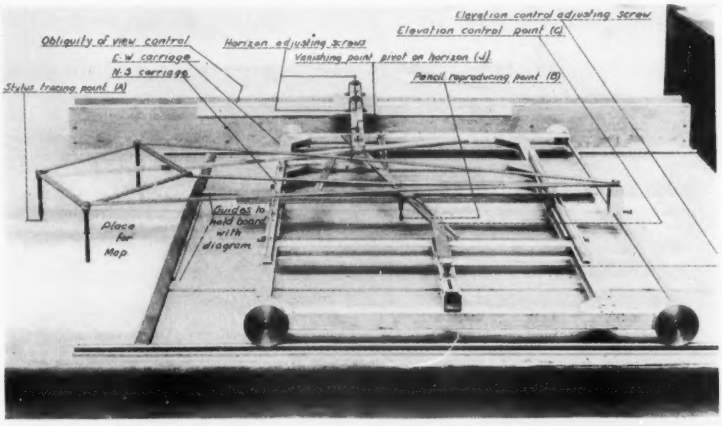



FIG. 6. The perspectograph assembled for use.

upward. There is one exception to this; the support of the pivot *J* for the arm controlling convergence is shown on Fig. 3 whereas in practise it is placed above the parts shown in Fig. 2. Fig. 6 shows the parts assembled for use.

AMHERST COLLEGE,
AMHERST, MASS.,
*July 17, 1940.*

# A TRIGONOMETRIC SOLUTION OF THE TWO-DRILLHOLE PROBLEM.

HERBERT A. STEIN.

ABSTRACT.

This paper deals with the calculation of the strike and dip of concealed bedding by means of a formula in terms of the angles made by the bedding and the axes of the cores of a vertical and an inclined drill hole.

## INTRODUCTION.

THE problem sometimes arises of finding the strike and dip of rock bedding that is completely covered by overlying rock masses or mantle rock. This information may be obtained by the interpretation of diamond drill cores.

It often happens that the drilling operations do not disclose a marker horizon. W. J. Mead[1] has presented a system for the solution of this case of the problem. The accuracy of this method depends upon the regularity and lack of close contortion of the bedding. Mead also discusses the limitations of the method, such as the conditions under which a number of possible solutions for the strike are obtained, and describes two methods of working out solutions from the data, namely, by descriptive geometry and by a mechanical device. The data may also be solved by means of graphs, a system proposed by E. Wisser.[2]

The purpose of the following article is to present a fourth method of solving the data, namely, by a trigonometric formula.

## THE DRILLING OPERATIONS.

A vertical hole is first drilled, and the core is taken where the hole cuts the bedded rock. The dip, which may be found directly

[1] Mead, W. J.: Determination of attitude of concealed bedded formations by diamond drilling. ECON. GEOL., 16: 37–47, 1921.

[2] Wisser, Edward: An aid in the interpretation of diamond drill cores. ECON. GEOL., 27: 437–449, 1932.

from a measurement on this core, is equal to 90° minus the core-bedding angle in the vertical drillhole core.

However, an unoriented core offers no information as to the strike of the bedding. To obtain the data necessary for the computation of the strike, one or two inclined holes must be drilled.

The first inclined hole yields data from which one, two, three, or four possible solutions for the strike may be calculated. In the event that more than one solution is produced, another inclined hole must be drilled in a different direction. The one solution reached by calculations from the data from both holes is the correct value of the strike.

Variation in the attitude of the bedding from place to place may cause an error in the computed value of the strike. This possible error may be minimized by drilling the inclined hole in such a manner that the core is taken from the bedded rock close to the point where the vertical drillhole core was taken.

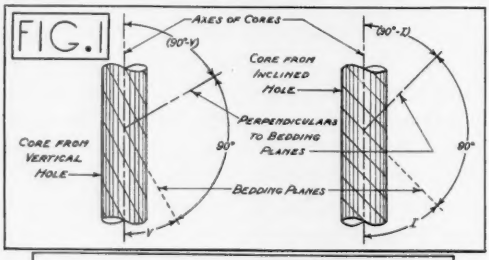
In the following derivation, the bearing of the downward plunging line that lies in the bedding plane and is perpendicular to the line of strike will be used, instead of the strike, to indicate the attitude of the bedding. This bearing, called the "direction of dip" throughout this paper, lies 90° away from the strike. The use of the direction of dip obviates the necessity of explaining the side of the strike line to which the bedding dips.

## DERIVATION OF THE FORMULA.[3]

The formula about to be derived will be an expression for $(E)$, the angle between the direction of dip of the bedding and the bearing of the inclined hole, in terms of $(H)$, the plunge of the inclined drillhole, $(V)$, the core-bedding angle in the vertical drillhole core, and $(I)$, the core-bedding angle in the inclined drillhole core. Hence, except when $(E)$ is equal to 0° or 180°, at least two possible solutions for the direction of dip are obtained, representing the calculated angle $(E)$ applied in either

[3] The derivation of the formula is presented in order to show the origin of the formula, and to illustrate the general method of deriving geological formulæ. It is not necessary to understand the derivation in order to use the formula.

direction, clockwise and counter-clockwise, from the bearing of the inclined hole. When $(E)$ equals 0° or 180°, there is, of course, only one possible direction of dip.



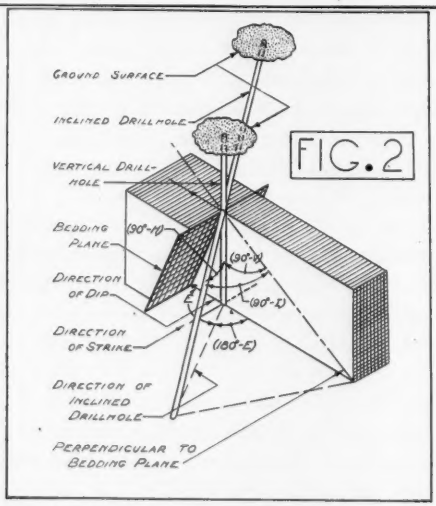




FIG. 1. How the drillhole cores are measured for the core-bedding angles $(V)$ and $(I)$.

FIG. 2. Diagram showing the geometric relations used in deriving the formula for one case of the problem.

Figure 1 illustrates how the drillhole cores are measured for $(V)$ and $(I)$, the core-bedding angles. This figure also shows that the angle between the axis of a drillhole and a perpendicular

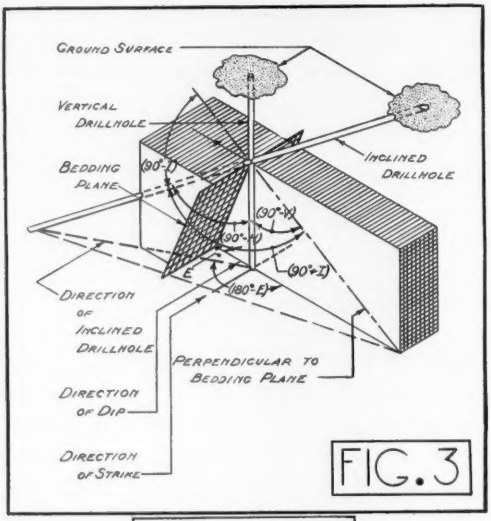
to the bedding plane is equal to 90° minus the core-bedding angle. This relation is used in Figs. 2 and 3.

There are two cases of the relative position of the bedding plane and the drillholes. In Fig. 2, the plane does not lie between the vertical and the inclined drillholes, as it does in Fig. 3. Sometimes, a value of $(E)$ may be obtained only in the first case, resulting in two possible solutions for the direction of dip. Other sets of data may give a value of $(E)$ in each case, resulting in four possible solutions for the direction of dip. Three possible solutions occur as a special case of four solutions, in which $(E)$ is equal to 0° for one set of solutions.

In order that all possible directions of dip may be obtained, a formula must therefore be derived for each of the cases shown in Figs. 2 and 3. In each of these figures, the drillholes are taken as intersecting, for geometric simplicity. This construction is consistent with the advisability of taking the vertical and inclined drillhole cores close to each other, in practice. Also, each of the figures shows only the bedding plane, the direction of dip of which lies to the clockwise of the bearing of the inclined hole. The other possible plane, the direction of dip of which lies an equal angular distance to the counter-clockwise, is omitted.

In Fig. 2, because the drillholes are both on the same side of the bedding plane, the angle $(90° - I)$ is measured between the drillhole and the perpendicular to the bedding plane on the same side of the plane as $(90° - V)$ is measured. Therefore, the angle $(90° - I)$ appears as the vertex angle of the front face of the triangular pyramid formed by the two drillholes and the perpendicular to the bedding plane. In Fig. 3, however, because the drillholes are on opposite sides of the bedding plane, the angles $(90° - I)$ and $(90° - V)$, which must be acute, are measured between the drillholes and the perpendicular on opposite sides of the plane. Hence, in Fig. 3, the vertex angle of the front face of the triangular pyramid is equal to 180° minus $(90° - I)$, or $(90° + I)$.

The required angle $(E)$, between the bearing of the inclined drillhole and the direction of dip of the bedding plane, may be



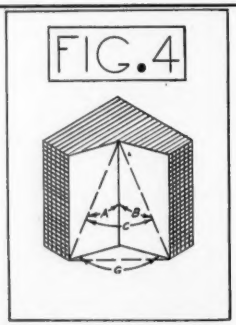




FIG. 3. Diagram showing the geometric relations used in driving the formula for the second case of the problem.

FIG. 4. Triangular pyramid with one edge vertical and the base horizontal.

found in terms of the given angles $(H)$, $(V)$, and $(I)$, by relating certain angles in the triangular pyramids referred to above.

The pyramid in Fig. 4 has the same characteristics as those in Figs. 2 and 3, namely, that the base is horizontal and one edge is

vertical. The following formula, the derivation of which will not be presented because it is purely mathematical, relates the angles of the pyramid in Fig. 4:

$$\cos G = \frac{\cos C}{\sin A \sin B} - \frac{1}{\tan A \tan B}. \qquad (1)$$

The following table lists the angles in Fig. 4, and the corresponding angles in Figs. 2 and 3:

| Description of Angles | Fig. 2 | Fig. 3 | Fig. 4 |
|---|---|---|---|
| One of the two face angles which include the vertical edge | $(90° - H)$ | $(90° - H)$ | $A$ |
| The other of these two face angles | $(90° - V)$ | $(90° - V)$ | $B$ |
| The third face angle of the pyramid | $(90° - I)$ | $(90° + I)$ | $C$ |
| The base angle lying at the point of intersection of the base and the vertical edge | $(180° - E)$ | $(180° - E)$ | $G$ |

We may now substitute in equation (1) the corresponding values for Fig. 2, shown in the table:

$$\cos (180° - E) = \frac{\cos (90° - I)}{\sin (90° - H) \sin (90° - V)} - \frac{1}{\tan (90° - H) \tan (90° - V)}. \qquad (2)$$

This relation simplifies down to the working formula for the case presented in Fig. 2:

$$\cos E = \tan H \tan V - \frac{\sin I}{\cos H \cos V}. \qquad (3)$$

In the same manner, substituting in equation (1) for Fig. 3, we get:

$$\cos (180° - E) = \frac{\cos (90° + I)}{\sin (90° - H) \sin (90° - V)} - \frac{1}{\tan (90° - H) \tan (90° - V)}. \qquad (4)$$

This reduces to the working formula for Fig. 3, which is essentially the same as that for Fig. 2, except for the sign which

joins the two expressions comprising the right half of the equation.

$$\cos E = \tan H \tan V + \frac{\sin I}{\cos H \cos V}. \qquad (5)$$

APPLICATION OF THE FORMULA TO THE SOLUTION OF PROBLEMS.

As previously explained, the measurements necessary for the use of the formula are:

$H$—the plunge of the inclined drillhole from horizontal
$V$—the core-bedding angle of the vertical drillhole core
$I$—the core-bedding angle of the inclined drillhole core.

The resulting angle, found by the substitution of these measured values in the formula given below, is:

$E$—the angle between the bearing of the inclined hole and the direction of dip of the possible planes of bedding lying to either side of the inclined drillhole.

In order to solve problems of the two-drillhole type, the observed values are substituted in the following formula, a combination of equations (3) and (5), which were derived in the previous section:

$$\cos E = \tan H \tan V \mp \frac{\sin I}{\cos H \cos V}.$$

The sign joining the two expressions in the right half of the above equation is a "minus or plus sign," indicating that both operations must be performed in order to obtain all possible values of $(E)$. If there are only two solutions for the direction of dip, for instance, only one of the two values of $(\cos E)$, obtained because of the minus or plus sign, will be within the limits of the cosine function, namely, $(-1)$ to $(+1)$.

The directions of dip of the possible planes of bedding are found by the application of the calculated value or values of $(E)$ in both directions, clockwise and counter-clockwise from the bearing of the inclined drillhole. The strike of each plane lies, of course, 90° from the direction of dip.

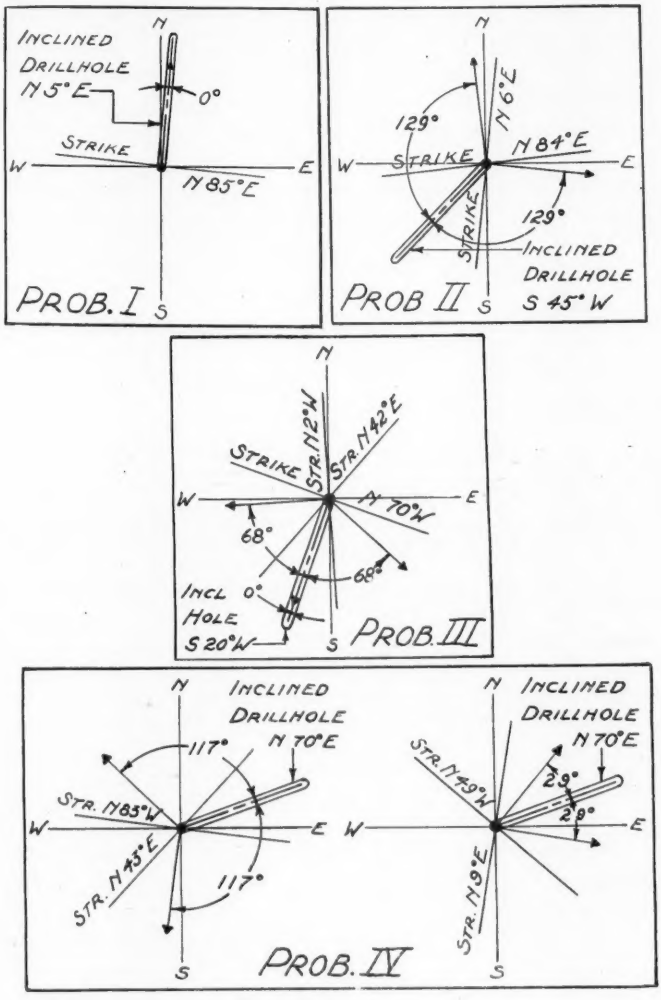



FIG. 5. Problems 1–4.

Following are the solutions of four problems, yielding one, two, three, and four solutions, respectively. Trigonometric tables of three decimal places were used, resulting in answers exact to the degree. A slide rule also yields results of this accuracy, which is usually sufficient for geological purposes. With each solution is a diagram showing the method of obtaining the required strike directions from the values of $(E)$ calculated by means of the formula.

EXAMPLES.

*Problem I.*

Observed data:

Bearing of the inclined drillhole = N. 5° E.
$H = 60°$ $V = 50°$ $I = 20°$

Calculations:

$$\cos E = \tan 60° \tan 50° \mp \frac{\sin 20°}{\cos 60° \cos 50°}$$

$$= (1.732)(1.192) \mp \frac{.342}{(.500)(.643)}$$

$\cos E = 2.065 - 1.064 = 1.001$ $E = 0°$
and and
$\cos E = 2.065 + 1\ 064 = 3.129$ no other value

Answers: Strike N. 85° W.
Dip 45° NE.

(One possible solution)

*Problem II.*

Observed data:

Bearing of the inclined drillhole = S. 45° W.
$H = 60°$ $V = 30°$ $I = 45°$

Calculations:

$$\cos E = \tan 60° \tan 30° \mp \frac{\sin 45°}{\cos 60° \cos 30°}$$

$$= (1.732)(.577) \mp \frac{.707}{(.500)(.866)}$$

$\cos E = 1.000 - 1.633 = -.633$ $E = 129°$
and and
$\cos E = 1.000 + 1.633 = 2.633$ no other value

| Answers: | | | |
|---|---|---|---|
| Strike | N. 6° E. | N. 84° E. |
| Dip | 60° SE. | 60° NW. |

(Two possible solutions)

*Problem III.*

Observed data:

Bearing of the inclined drillhole = S. 20° W.
$H = 50°$ $V = 30°$ $I = 10°$

Calculations:

$$\cos E = \tan 50° \tan 30° \mp \frac{\sin 10°}{\cos 50° \cos 30°}$$

$$= (1.192)(.577) \mp \frac{.174}{(.643)(.866)}$$

$\cos E = .688 - .312 = .376$ $E = 68°$
and and
$\cos E = .688 - .312 = 1.000$ $E = 0°$

| Answers: | | | |
|---|---|---|---|
| Strike | N. 42° E. | N. 2° W. | N. 70° W. |
| Dip | 60° SE. | 60° SW. | 60° SW. |

(Three possible solutions)

*Problem IV.*

Observed data:

Bearing of the inclined drillhole = N. 70° E.
$H = 50°$ $V = 10°$ $I = 25°$

Calculations:

$$\cos E = \tan 50° \tan 10° \mp \frac{\sin 25°}{\cos 50° \cos 10°}$$

$$= (1.192)(.176) \mp \frac{.423}{(.643)(.985)}$$

$\cos E = .210 - .668 = -.458$ $E = 117°$
and and
$\cos E = .210 + .668 = .878$ $E = 28°$

| Answers: | | | | |
|---|---|---|---|---|
| Strike | N. 9° E. | N. 43° E. | N. 49° W. | N. 83° W. |
| Dip | 80° SE. | 80° NW. | 80° NE. | 80° SW. |

(Four possible solutions)

ACKNOWLEDGMENT.

I should like to express my thanks to Dr. Warren J. Mead for introducing this problem to me, for the loan of his mechanical device with which I was able to check the results of the formula, and for his help in preparing this paper.

MASSACHUSETTS INSTITUTE OF TECHNOLOGY,
CAMBRIDGE, MASSACHUSETTS,
*June 19, 1940.*

# DISCUSSION AND COMMUNICATIONS

## *MAGNETITE IN SULPHIDE ORES.*

*Sir:* The paper of this title by G. M. Schwartz and A. C. Ronbeck, pp. 585–610 of volume 35 of the Journal, was of particular, and most timely, interest to me as I have just now encountered magnetite that appears to be later than the pyrite with which it is associated in a gold-quartz vein of the Lupa Goldfield, Tanganyika Territory, East Africa.

In Table II Schwartz and Ronbeck list "52 districts on which enough detailed work has been done to indicate the order of formation of the principal ore minerals." Magnetite is the first mineral to form in most cases, but in eleven cases it is not the first mineral. These were obviously of great interest to me at the moment, and seeking further information I referred back to the original references given by Schwartz and Ronbeck.

These eleven districts are quoted in Table II as follows:

| District | Order of Formation of Minerals |
|---|---|
| Ak-tyus, Russia | Py, C, A, Mr, H, M, S, Pr, Cp, St, G |
| Ehrenfriedensdorf, Germany | W, C, A, M, Pr, S, Ca, Cp, Py, He |
| Hitachi Mine, Japan | Py, S (CpPr) (PyMr) M |
| Horne Mine, Que. | Py, M, Pr, S, Cp, G, Au, Te or Py, Pr, M, Cp, Au, Te |
| Kaveltorp, Sweden | (Mo, Py, A) (S, Pr, Cp) Cu (S, Py, Cp) G, B, M<br>Hydrothermal Py, Cp, Ga, M, Va, Mr, Cu |
| Michipicoten, Ont. | Py, Pr, Cp, M |
| Northpines Mine, Ont. | Py, M, Pr (CpS) |
| Panamint District, Calif. | Py, Pr, Cp, M |
| Roros, Norway | Py, Cp, Pr, S, M, B, Cc, G (or M earliest) |
| Rouyn, Que. | Py, M, Pr, S, Cp, Py |
| San Carlos Mts., Mexico | (Py, Cp) M |

Unfortunately the paper by Volynski on the Ak-tyus deposits is not available at the moment, but the paragenetic sequence is evidently so unusual and so complex that its significance is not readily explainable. Similarly, the Ehrenfriedersdorf (spelled two other ways by Schwartz and Ronbeck) deposit is, according

to Franke's description, extremely complicated. Even if it is admitted that the criteria for the age determination of minerals are sufficiently certain so that thirty-eight minerals can be arranged in a definite paragenetic diagram, the physico-chemical mineralogy involved is too complicated for a full comprehension of the mineralization process in all its details.

Franke's sequence is given as quartz, wolframite, lepidolite, topaz, tourmaline, cassiterite, raimondite, arsenopyrite, arsenoferrite, gilbertite, molybdenite, fluorite, paradoxite, apatite, beryl, herderite, phenacite, triplite, chlorite, siderite, oligonite, rhodochrosite, apatite, gilbertite, scheelite, magnetite, pyrrhotite, sphalerite, cassiterite, chalcopyrite, anatase, galena, quartz, fluorite, pyrite, hematite, lithomarge, and nacrite. Despite its complexity this series suggests that deposition took place with falling temperature that reached a low point in the deposition of the carbonates, and that then there ensued a sudden increase in temperature, or a second period of mineralization, in which the magnetite occupied its more customary place as an oxide preceding the sulphides.

One might be led to suppose from the definite presentation of Table II that the order of formation of the minerals at the Hitachi Mines was fully established as given, but Watanabe and Landwehr state (p. 441) " Galena and magnetite occur in such small amounts that their relation to other minerals is not determinable."

According to Price, the mineralization at the Horne mine began with pyrite, then

> . . . the sulphur content in the solutions either fell below the point where pyrite would form, or else a new accession of material came in, which was low in sulphur. At any rate, the minerals next to be deposited were magnetite, pyrrhotite, and chalcopyrite. All three of them vein the pyrite, and though there were certain reversals and repetitions . . . it is believed that they were formed essentially in the order named. A certain amount of pyrite was deposited late in the series.
>
> There is considerable evidence to show that the three minerals were fairly closely related in age. Further, it is believed that there was a definite lull, if not an actual break, in the mineralization period after the deposition of the pyrite and before the appearance of the three later minerals.

It is noteworthy that after this distinct change or interruption

in the deposition, the magnetite appeared in its more customary place preceding the sulphides.

Ödman's description of Kaveltorp reveals a weakness in the abbreviated notation used by Schwartz and Ronbeck. An ideal system of abbreviation should enable the presentation of the full story in small space without any sacrifice of accuracy; but the second Py, although it may be intended to indicate the hydrothermal pyrite, is a little difficult to reconcile with Ödman's data, and the magnetite given at the end of the first series appears to be misplaced. In any form this abbreviated notation does not reveal the important point regarding the magnetite. Ödman goes into considerable detail in discussing the unusual origin of the magnetite at Kaveltorp. He believes that it was derived by the break down of sulphides, particularly cubanite, during a late phase of the mineralization. The Ga means gangue and B means bornite, according to the key at the end of Table II, but here they apparently mean galena and bismuth. Ödman's paragenetic diagram is as follows:

| Mineral | Primary mineralization | Hydrothermal | Supergene |
|---|---|---|---|
| Molybdenite | — | | |
| Pyrite | — | —— | .... |
| Arsenopyrite | —:.. | | |
| Sphalerite | ——— | | |
| Pyrrhotite | —— .... | | |
| Chalcopyrite | ——— | —— | |
| Cubanite I | —— | | |
| Galena | ... ——— | —— | |
| Bismuth | — | | |
| Magnetite | | —— | .... |
| Valleriite | | —— | |
| Marcasite | | .... | —— |
| Cubanite II | | .... | |
| Limonite | | .... | —— |
| | 575° 450° 270° | | |

In Mac Murphy's paper on the Panamint District he mentions magnetite only once:—in the petrographic description of the Little Chief Porphyry in which magnetite is one of the accessory minerals. No magnetite occurs in the ores of the Michipicoten

district according to Frohberg's description. However, both districts contain late marcasite, and the M at the end of each of these two sequences in Table II can thus be explained; but neither deposit should have been included in a paper on magnetite. This suggests another weakness in this system of abbreviated notation. Frohberg's paragenetic diagram lists seventeen minerals in all, including non-metallics, and bears little, if any, resemblance to the " Py, Pr, Cp, M " of Table II.

The sequence given in Table II for Roros, Norway, is difficult to reconcile with the data given by Carstens. For the Roros type, which is one of four types of deposits described by Carstens, he gives the following sequence:

> Magnetit—immer das älteste Mineral,
> Schwefelkies,
> Zinkblende,
> Magnetkies,
> Kupferkies,
> Bleiglanz—immer das jüngste Mineral.

The data of Table II is in agreement with the data of the authors cited for the Northpines mine, the Rouyn district, and the San Carlos Mountains, and these three appear to be clear cases in which pyrite preceded magnetite.

In summary, then, what appeared to be eleven exceptions to the usual order wherein magnetite precedes the sulphides, may be reduced to three. Ak-tyus and Ehrenfriedersdorf are too complicated to be interpreted although both may contain a break in the sequence after which the magnetite behaved normally. Likewise the Horne mine may be explained by a break in the depositional process. At Kaveltorp the magnetite had a highly specialized origin. At Hitachi the relations are unknown; no magnetite occurs at Michipicoten or Panamint; and magnetite was the first mineral to form at Roros; leaving the three clear cases of Northpines, Rouyn, and the San Carlos Mountains.

In all three of these deposits only a little pyrite formed before the magnetite, and the main bulk of the sulphide deposition continued on, long after the magnetite had ceased to form. In all three there was only a very small difference in time between the

first pyrite and the magnetite. Furthermore, all three are high temperature replacement deposits, and are either actually pyrometasomatic deposits or closely akin to that type. In such deposits the invaded rocks probably undergo a period of pre-heating before the advent of the main mineralizing solutions. It is possible that tenuous fore-runners of the main mineralization, capable of carrying and depositing small amounts of pyrite, preceded the magnetite and sulphide-bearing solutions that deposited the main bulk of the ore.

Thus, a compilation of fifty-two cases, of which eleven (or 20 per cent) appeared to be exceptions to the old, and abundantly supported idea that magnetite preceded the sulphides, may be reduced to such an order that the old rule still stands. The cases cited would suggest the conclusion that magnetite forms before the sulphides, except that (1) it may appear in the middle of a complex sequence in which more than one episode of ore deposition is involved, although even here it is actually the first mineral of the sequence to which it belongs genetically, and (2) a little early sulphide may be deposited by the tenuous fore-runners of the main ore-forming solutions in the case of some pyrometasomatic deposits. Although such a conclusion fits the facts presented by Schwartz and Ronbeck, it is at best only valid in a general way as being true in most cases, for there are exceptions not listed in Table II, but they are rare. For example, B. S. Butler describes and figures a very convincing case of magnetite surrounding chalcopyrite in a pattern resembling reaction rims, from the pyrometasomatic deposit of the Imperial mine, Utah (U. S. Geol. Surv., Prof. Paper 80, p. 84). Similar material is noted as found by A. C. Spencer in the Ely district, Nevada. A more thorough search of the literature might reveal many more examples.

The synthesis and coordination of data, as undertaken by Schwartz and Ronbeck, is work of the highest value, and it is to be hoped that much more will be forthcoming. However, a better system of notation seems advisable, for the present system readily admits errors, conceals the significance of the facts, and

may even obscure or distort the facts themselves. In concluding it is impossible to refrain from mentioning the unusually large number of small errors in Schwartz and Ronbeck's paper, that are not attributable to the shortcomings of their abbreviated notation; for example, reference number 36 alone contains five errors.

DAVID GALLAGHER.

LABORATORY OF ECONOMIC GEOLOGY,
YALE UNIVERSITY, NEW HAVEN, CONN.
*August 10, 1940.*

## *MAGNETITE IN SULPHIDE ORES.*

*Sir:* The article by Schwartz and Ronbeck on "Magnetite in sulphide ores" in your August issue[1] distinctly misstates the relationships of various minerals at Balmat, N. Y., as described in my paper, which they cite as their source of data,[2] incidentally also misquoting the title of the paper by substituting Millerite for Willemite (p. 606). No millerite is known at Balmat.

The article states (p. 599) that "sphalerite and hematite replace magnetite at Balmat, N. Y., and finely divided magnetite occurs as a matrix in sphalerite." Actually, there are two very different sphalerites at Balmat. The later variety, secondary to the earlier, I interpreted as contemporaneous with hematite and magnetite, and all three very definitely replace the original primary sphalerite and pyrite as well as gangue. It is possible that sphalerite (secondary, not primary) and hematite may have replaced some of the magnetite, but I made no such interpretation and know of no evidence to support it.

Additional statements (p. 597) seem to be correctly recorded, but the interpretation that this magnetite is supergene, and low-temperature, is ignored.

JOHN S. BROWN.

EDWARDS, NEW YORK,
*Sept. 3, 1940.*

[1] Schwartz, G. M. and Ronbeck, A. C. Magnetite in sulphide ores. ECON. GEOL., Vol. 35, pp. 585–610.

[2] Brown, J. S. Supergene sphalerite galena and willemite at Balmat, N. Y. ECON. GEOL., Vol. 31, pp. 331–354, 1936.

# REVIEWS*

**The Principles of Economic Geology.** By WILLIAM HARVEY EMMONS. Pp. 529 + xix; Figs. 329. McGraw-Hill Book Company, New York and London, 1940 (Second Edition). Price, $6.50.

At first glance this revision resembles the earlier edition. Like that volume, it is well printed, has convenient sub-headings, and is amply documented, and generally well illustrated. A few more photographs (there are only eleven) of typical ores, in place of or supplementary to some of the numerous sketches, would convey a sense of reality that the many generalized diagrams showing geographic distribution, cross-sections, and geologic columns do not quite supply. The literary style and contents are terse and pointed, and, to the reviewer, they strike a happy balance between scientific punctiliousness and practical simplicity that should commend the book to a wide audience. This volume is thicker but has actually fewer pages than the first edition though there are more lines to the page and smaller spaces between sections.

There has been a marked increase in *pithiness* and a reduction of the more conventional discussions, in general a distinct gain. Locally this change involves slight sacrifices in clarity, as on page 1, where, without further explanation 1 gram is said to equal "$1.125 U. S. currency (1939)" and 1 troy ounce to equal "$35 U. S. currency (1939)," no statement being made to the effect that these are the values of the corresponding weights *of pure gold*. Such a table of equivalents, by the way, might well have included the values of long, short, and metric tons and of kilos, in view of the widespread price quotation of ores in those terms and the variations in the unit with the country. Indeed, for an American, called upon to work in Latin America, the equivalent values of hektares and of kilometers are highly useful.

Meriting special comment is the obvious effort made by the author to bring the text into accord with modern views, yet remain judicial for the sake of the student. Thus, his mention of the telethermal ores under "Deposits formed by cold meteoric solutions" (p. 81) is obviously a laudably conservative attempt to present both sides of a thorny question.

Still more valuable to the reviewer is the significance attached by the

* Books noted under *Reviews* and *Books Received* may be ordered through the Economic Geology Bookshop, W. S. Bayley, Urbana, Ill., but orders for official reports and single copies of Journals should be sent directly to their publishers.

author to structural control of ore deposition. On this score the volume bears striking testimony to the growth of the author, whose original interests, as judged by earlier publications, lay more nearly in the field of the chemistry of primary deposition and of enrichment. The systematic chapters dealing with each class of ores (magmatic segregates, pegmatites, and the like) are all sharpened and made more significant by diagrams that emphasize the structural outlook. A special chapter, "Structural Control of Epigenetic Deposits," has been added, the second longest chapter in the systemic part of the text.

The excellent discussions of deposits, classified by metals (pp. 234–472), which has been retained in its essentials from the earlier edition, is enriched by more concrete and realistic diagrams of individual districts that serve to clarify the accompanying descriptions. Diagrams are especially well designed for the sections on copper and of the precious metals; in the copper section illustrations have been more than doubled in number, an obviously wise concession to the effectiveness of visual education. The introduction of more descriptions of foreign districts is also a desirable change; for the experienced American geologist descriptions of foreign deposits frequently represent the chief value of a general handbook, and for the beginner the comparison of foreign and local deposits serves to emphasize the ubiquity of the laws of ore deposition. The little sketch map of the United States showing the larger copper deposits (Figure 205, page 279) is very convenient. Similar ones would be useful for the other metals; eastern students in particular show a deplorable ignorance of the *geography* of ore deposits.

There are two general needs in texts of economic geology which the reviewer is here tempted to suggest. Few afford to the tyro mining geologist (as distinct from the academic or survey employee) the *practical* viewpoint needed for his profession. Obviously no text can be "all things to all men." But the reviewer's own experience as field worker and teacher indicates that there might profitably be incorporated in each such text (1) a chapter devoted to underground geologic technique, including mapping (*not* surveying, in the engineering sense; for that the student may be referred to other courses and texts), sampling, and geologic interpreting, and (2) a chapter on the economic factors involved in a geologic appraisal of the deposit. Knowledge, judgment, and skill would be required in such writing; Dr. Emmons has all three qualities and it is to be hoped that he will add these sections in a future revision or supplement.

One or two details might be altered to advantage. A distinction is recognizable between "secondary" and "supergene," though, as by many others, none is made (page 6); thus, the Joplin ores are supergene, according to Siebenthal, but scarcely secondary. The arrangement used on

page 6 suggests that magmatic segregates are a type of epigenetic deposit, whereas this is certainly not intended. Certain other details, such as citations of publications by Sachs and Gurich for details of the Silesian ores when much more authoritative and recent works are available, are also minor short-comings. But these errors, while of interest to the specialist, detract but little from the book as a standard reference and none whatever as a text.

Despite these suggestions for change, despite minor criticisms, the reviewer regards the book as excellent. It is adaptable to students at several different levels. For the practising geologist it correlates world-wide observations and opens vistas that are both informative and stimulating. In brief, it deserves an honored place among the classical handbooks of economic geology.

CHAS. H. BEHRE, JR.

NORTHWESTERN UNIVERSITY,
EVANSTON, ILL.,
*January 13, 1940.*

**Geophysical Exploration.** By C. A. HEILAND. Pp. 1013; Figs. 570. Prentice-Hall, Inc., New York, 1940. Price, School, $3.00, Trade, $10.00.

This large volume is a comprehensive survey of the entire field of geophysical exploration presented in broad perspective. It contains an interesting innovation in that Part I (64 pages) is written in simple language for those in executive or advisory capacity who desire some insight into the working principles and geologic applications, and Part II, the meat of the volume is written for the technical student of geophysics, with particular attention to correlation between geology and geophysics. The fundamental principles are treated thoroughly and field, office, and laboratory methods are described briefly. Application to various engineering problems is pointed out. Many good drawings and a few poor photographs supply much pictorial information.

The book appears to contain everything that one would care to look up on geophysical exploration and should prove to be the standard reference book on the subject. It is rather striking that two good books on geophysical exploration should appear almost simultaneously.

**Chambers's Technical Dictionary.** Edited by C. F. TWENEY AND L. E. C. HUGHES. Pp. 957. Macmillan and Co., New York, 1940. Price, $5.00.

This new and comprehensive dictionary compiled by a staff of 37 experts contains thousands of terms drawn from about a hundred branches of

scientific and technologic activity. It gives definitions of terms in pure and applied science, engineering, mechanics, construction and manufacturing. It is a technical dictionary compiled by specialists for specialists, students and all interested. Many of the terms are formulated for the first time; others have never before appeared in a handy work. Many common words that have lately attained technical significance are included.

In geology, all mineral names, rocks, fossils, petrologic terms, stratigraphic names, and other geologic terms are included and other subjects are similarly treated. At the back are tables of chemical elements, igneous, sedimentary and metamorphic rocks, plants and animals, and a bibliography of the various subjects.

The volume is one that every scientific worker and student in science and technology will welcome and use. The authors and publishers are to be congratulated for this stupendous task.

**Exploration Geophysics.** By J. J. JAKOSKY. Pp. 786; Figs. 411. Times Mirror Press, Los Angeles, Calif., 1940.

This book deals with the fundamental theories, equipment and field practice of the various geophysical methods. Different chapters deal with the background, magnetic, gravitational, electrical, seismic, geochemical, geothermal methods, drill hole investigations (logging methods) and physical principles applied to production problems. Each chapter has been submitted to experienced reviewers, of whom a list is published. Numerous photographs and drawings help make the subject matter clear. The volume appears to be thorough, well organized and practical.

## BOOKS RECEIVED.

WILLIAM E. BENSON.

**Revista de Fomento.** Pp. 346; numerous unnumbered pls. and figs. EE. UU. de Venzuela, Min. de Fom., Año III, No. 19. Caracas, 1939. *Several papers presenting the results of an exploration of part of Bolivar.*

**Spirit Leveling in Utah, 1897–1938.** J. G. STAACK. Pp. 222; pls. 2. U. S. Geol. Surv., Bull. 912. Washington, 1940. Price, 30 cents.

**Geology and Ground-Water Resources of the Harney Basin, Oregon.** A. M. PIPER, T. W. ROBINSON, AND C. F. PARK, JR. Pp. 189; pls. 19; figs. 9; geol. map in color 27″ × 32″, scale 1:125,000. U. S. Geol. Surv., W. S. P. 841. Washington, 1939. Price, $1.00. *A semi-arid, interior drainage basin.*

**The Floods of December 1937 in Northern California.** H. D. MCGLASHAN AND R. C. BRIGGS. Pp. 505; pls. 13; figs. 74; tables 18. U. S. Geol. Surv., W. S. P. 843. Washington, 1939. Price, 60 cents.

**Generalized Section of Coal Bearing Rocks of Ohio.** W. STOUT. One table, 8½″ × 26″, folded. Ohio Geol. Surv., Info. Circ. No. 2. Columbus, 1939. *Stratigraphic section with thicknesses and comments on the coal beds.*

**Geology of the Chicago Region, Part I—General.** J. H. BRETZ. Pp. 112; pls. 8; figs. 91. Illinois Geol. Surv., Bull. 65, Pt. I. Urbana, 1939. *Part I deals with the general and glacial geology in a style suited for use by the layman and in schools. Beautifully printed and illustrated. Glacial geology map in color, 12″ × 27″, scale probably about 1:31,680.*

**Glass Sands and Molding Sands.** J. A. BOWNOCKER. Pp. 54. Ohio Geol. Surv., Reprint Ser., No. 2. *Discusses sand specification and Ohio production.*

**Geology of the Country around Gwanda.** R. TYNDALE-BISCOE. Pp. 204; pls. 15; figs. 14; geol. map in color, 20″ × 31″, scale 1:100,000. Southern Rhodesia Geol. Surv., Bull. 36. Salisbury, 1940. Price, 6s. 10½d. *Detailed general geology, particularly petrography and petrology, and descriptions of mines with plans and sections.*

**Tabulated Analyses of Texas Crude Oils.** A. J. KRAEMER AND G. WADE. Pp. 37; 1 fig. U. S. Bur. Mines, Tech. Paper 607. Washington, 1939. Price, 15 cents.

**Comparative Tests of Various Fuels when Burned in a Domestic Hot-Water Boiler, 1935 to 1938.** C. E. BALTZER AND E. S. MALLOCH. Pp. 23; 1 pl.; figs. 3. Canada Bur. Mines, No. 802. Ottawa, 1940. Price, 25 cents.

**Tests on the Liquefaction of Canadian Coals by Hydrogenation.** T. E. WARREN AND K. W. BOWLES. Pp. 106; pls. 2; figs. 3. Canada Bur. Mines, No. 798. Ottawa, 1940. Price, 25 cents.

**The Devonian of Pennsylvania.** B. WILLARD, F. M. SWARTZ, AND A. B. CLEAVES. Pp. 481; pls. 32; figs. 96. Penn. Geol. Surv., 4th Ser., Bull. G 19. Harrisburg, 1939. *Detailed and exhaustive treatise on the stratigraphy and paleontology.*

**Diatomito do Nordeste.** H. C. A. DE SOUZA AND S. F. ABREU. Pp. 56; pls. 16; figs. 3. Brazil Div. de Fom. da Prod. Min., Bol. 33. Rio de Janeiro, 1939.

**Piritas de Rio Claro.** H. C. A. DE SOUZA. Pp. 30; pls. 5; figs. 2. Brazil Div. de Fom. da Prod. Min., Bol. 34. Rio de Janeiro, 1939.

**Reconhecimento Geomagnético nos Arredores do Planalto de Reserva, Estado do Paraná.** D. S. ODDONE. Pp. 39; figs. 19. Brazil Div. de Fom. da Prod. Min., Bol. 35. Rio de Janeiro, 1939.

**Developments in Coal Research and Technology in 1937 and 1938.** A. C. FIELDNER. Pp. 95. U. S. Bureau Mines, Tech. Paper 613. Washington, 1940. Price 10 cents. *The publication of this interesting review as a part of the Minerals Yearbook was discontinued in 1938 but has been resumed as a separate publication in response to popular demand. A wealth of data, particularly on synthetic fuels and oil, with about one thousand references.*

# SOCIETY OF ECONOMIC GEOLOGISTS

*Abstracts of Papers to be Presented at the Twenty-first Annual Meeting in Conjunction with the American Institute of Mining and Metallurgical Engineers, New York, February 17–20, 1941.*

## *SOME COMPARISONS OF SUDBURY WITH THE BUSHVELD COMPLEX.*

E. S. MOORE.

The Bushveld Complex is on a much vaster scale than the Sudbury nickel-intrusive but both have a number of features in common. Both areas have had a complex geological history leading up to the formation of the ore deposits, and the intrusives from which these were derived were preceded and followed by extensive igneous activity. Pseudo-stratification is evident in the intrusives from which the ore deposits are believed to have been derived but is far more highly developed in the Bushveld. In the Bushveld the main ore deposits occur in two distinct types; stratified and pipe, whereas in the Sudbury area the distinctly stratified type is absent and only one or two deposits approach pipelike form. The ore body in one of the old mines at Copper Cliff was of this type. In the Bushveld both nickel and platinum occur in funnel-shaped deposits. Nickel-copper ore is dominant at Sudbury with platinum important, but subsidiary, whereas in the Bushveld chromite, titaniferous magnetite and platinum are dominant with nickel-copper ore subordinate. The more basic nature of the noritic phase of the Bushveld Complex seems to have been an important factor in the character of the ore deposits formed. The micropegmatite of the Sudbury nickel-intrusive is remarkably similar in texture to that of the granophyre in the Bushveld. The complex of Montana shows some features intermediate between those of the areas described.

## *DYNAMIC ORE CONTROL.*

EDWARD WISSER.

Structural factors that localize ore shoots in metalliferous veins may be classified as (1) static and (2) dynamic. A preëxisting permeable portion of a fracture, filled with ore and gangue to the exclusion of the tight portions, is an example of static ore control. Intra-mineral fault movements along a vein fracture, or its gaping as vein matter enters it, are types of dynamic ore control.

Such intra-mineral movements are generally slight quantitatively, but they may represent the end-stage of a unit process of deformation operative over a wider area than that of the neighborhood of any one vein, and of a process sufficiently vigorous at its height to permit perhaps evaluation

in terms of permeable spaces produced. If the commercially important end-stage retains the characteristics of the stronger phase of deformation preceding it, tendencies toward fracture opening and sealing recognized from study of the stronger phase may be extrapolated into the closing weak phase, with resulting hints on ore localization not derivable from examination of one vein and its immediate surroundings alone.

Many fracture patterns are not decipherable, but a few types stand out as commonly resulting from certain kinds of regional deformation (*e.g.* uplift, collapse, folding etc.). Using these types as "controls" a number of mining districts are analyzed from the standpoint of tectonics and mineralization; interrelations of those two processes are revealed, and new light, it is hoped, thrown upon the puzzle of why ore is where it is.

## *HOST-ROCK INFLATION BY VEINS AND DIKES AT GRASS VALLEY, CALIFORNIA.*

ROLLIN FARMIN.

Structural deformation of the rocks along the western Sierra Nevada has developed zones of faulting and of minor partings that are only slightly dilatant, appropriate for deep-seated environment. The gold-quartz veins and dikes of igneous rocks occupy partings of highly dilatant character in the country rocks and contain fragments of them as inclusion breccias—features that may result from the inflation of deep-seated rocks by an injected fluid but are not associated with deep-seated faulting. Evidence for the folding of inter-vein and inter-dike slabs of wall rock during inflation of the partings is described and is considered discordant with an open-fissure environment. Most of the structures found in the gold-quartz veins are duplicated in igneous dikes of comparable size—parallel mechanisms of emplacement are inferred.

## *GEOLOGY OF THE OMEGA MINE, LARDER LAKE, ONTARIO.*

C. P. JENNEY.

The Larder Lake district lies along a narrow band of Timiskaming sediments that extend from Kenogami, Ontario, east to beyond the Bell River in Quebec. On the Omega property lavas and tuffs of the underlying Keewatin outcrop in the middle of this band in a sharply folded anticline overturned to the north. This anticline is broken by a thrust fault that follows the strike of the fold and along which the volcanics and sediments of the south limb have been up-thrown.

Later dikes and larger masses of granite, syenite, porphyry and lamprophyre intrude the older rocks. The Omega ore is, in part, an intrusive pegmatite of granitic composition, which came in along the thrust fault on the hanging wall or south side, and an irregular replacement of the country rock (usually a green dacite) both adjacent to the intrusive and in a flow or flows on the northern limb of the structure. End stage volcanic action involved the introduction of large volumes of carbonates that completely or partially altered zones of the country rock to calcium, magnesium and iron carbonates.

## SECONDARY MAGNETITE IN SEDIMENTARY IRON ORES.

ALBERT O. HAYES.

Magnetite, due principally to metamorphism of hematite and chamosite, is described from a number of localities in the United States and Canada. Contact metamorphism is the cause in one deposit in Nova Scotia; the others appear to be due to folding under load.

In the Nictaux-Torbrooke Iron District, Nova Scotia, oölitic hematite-chamosite-carbonate ores of Oriskany age crop out on two limbs of a closely folded syncline. Post-ore granite cuts the south limb. The iron minerals within a half mile of the contact are altered to magnetite. At greater distances they are progressively less changed and in some beds little magnetite has developed. The gradation proves contact metamorphism to be the main cause, but magnetite due to kinetic or static metamorphism, if present, cannot be distinguished. Secondary magnetite in oölitic ores where no surface evidence of igneous intrusion has been observed, is thought to be caused by kinetic metamorphism. Such ores occur at Arisaig, Nova Scotia, where beds of oölitic ore of Ordovician and Silurian age crop out two miles apart. The Neda iron ores of Mayville, Wisconsin, of Upper Ordovician age, and the oölitic hematite of the Reagan sandstone, of Upper Cambrian age in Oklahoma, hold small amounts of secondary magnetite, probably developed under load, as no intrusive rocks are found in the vicinity.

Magnetite is reported from the early Paleozoic oölitic iron ores of France and Wales but none has been described from the Wabana ore of Newfoundland, nor has it come to the writer's attention in descriptions of the Clinton iron ores of the eastern United States. Secondary magnetite may be found in these ores on closer study, for small amounts of magnetite are easily mistaken for hematite under the microscope.

## OÖLITIC PYRITE, WABANA, NEWFOUNDLAND.

HOWELL S. JOBBINS.

(Introduced by A. O. Hayes)

Oölitic bedded pyrite accompanies the sedimentary iron ore deposits of Bell Island, Conception Bay, Newfoundland. Diamond drill cores through some 900 feet of the iron ore bearing strata have been examined and the oölitic pyrite horizon found. In this paper the results of a study of 336 feet of the core through the pyrite zone and accompanying strata are presented. Emphasis is on the mineralography of the pyrite and an interpretation of the rhythms in the accompanying sediments.

The oölitic pyrite occurs as a definite zone in marine graptolitic shale above the lowest workable iron ore beds and varies in thickness from 1 inch to 10 feet. As proved in mining operations, it persistently accompanies the underlying oölitic hematite. The pyrite is mostly oölitic but crystalline forms are found. Pseudomorphs of pyrite after shell fragments, calcite, quartz, etc., are plentiful. Some of these indicate replacement in part during sedimentation before the material came to rest while others were pyritized after the bed was formed.

The pyrite is embedded in a finely crystallized quartz. Broken oölites of pyrite contain veinlets of quartz continuous with the matrix. The

unbroken quartz indicates post pyrite crystallization. While chemical history of the quartz can only be inferred its relation to the pyrite suggests the development of a gel in the sea bottom muds and later crystallization.

## *ENGINEERING GEOLOGY OF THE CANTON RESERVOIR PROJECT SITE.*

EDWARD B. BURWELL, JR., AND DAVID E. LOUGHRAN.

(Introduced by David G. Thompson)

The site of the proposed Canton Reservoir, one of the authorized flood control projects of the United States Army Engineers, is located in the Permian red beds of Oklahoma on the North Canadian River. Soft, uncemented rocks underlie the site to great depths. Some of the formations contain vast quantities of soluble matter, chiefly gypsum and salt. Partial removal of the soluble matter has resulted in wide spread slumpage and disturbance. Extensive deep explorations were made to determine the extent to which the processes of solution and fill are now complete in the site area and the permeability and consolidation characteristics of the materials thus affected. The proximity of the Cimarron River valley, whose floor lies 400 feet below that of the North Canadian River, has facilitated deep removal of easily soluble matter over wide areas. That the greater part of the solution and fill took place ages ago under a considerable load of superincumbent material is evidenced by the well-compacted condition of the disturbed materials and the presence in some of the zones of slumpage of materials of Cretaceous age. The paper describes briefly the geology of the area, discusses the engineering geology problems and outlines the investigations undertaken to prove the geologic feasibility of the site.

## *ENGINEERING GEOLOGY IN THE PROGRAM OF THE TENNESSEE VALLEY AUTHORITY.*

BERLEN C. MONEYMAKER.

Engineering geology has a large-scale application in the program of the Tennessee Valley Authority (T.V.A.). The Authority, which is currently engaged in the construction of several large dams on the Tennessee River and its tributaries, maintains one of the largest engineering geologic staffs in the world. In the planning of projects, the engineer and geologist work jointly and the dam sites tentatively selected for further consideration are those that best meet all requirements. A geologic field party, usually consisting of two men, is maintained at each project continuously during the preliminary investigation, exploration, and construction stages. In all of these stages, close coöperation is maintained between the engineer and geologist. By the construction of hundreds of detailed drawings, supplemented by numerous daily discussions, the geologist is able to acquaint the engineer, in advance, with all geologic conditions that must be met by design, foundation preparation, or foundation treatment.

In addition to his duties at the dam site, the engineering geologist engages in other activities related to his project, including the location of construction materials, malaria control, mineral appraisals, ground water problems, and relocations of various kinds.

## ARTESIAN CONDITIONS IN THE LOWER TENNESSEE VALLEY.

ROGER RHOADES.

The lower Tennessee River, flanked by moderate highlands, flows in a broad valley whose bedrock floor is deeply buried by fluviatile sediments.

Ground water migrating from the highlands toward the river travels through (1) circuitous solution channels in the buried limestone bedrock and (2) the superjacent alluvial sediments (by interstitial flow) these aquifers possessing artesian pressures which, while related, differ in magnitude and manner of development.

The uppermost sediments of the flood plains are silty clays of limited permeability. These clays form an impervious "roof" over the underlying flood plain sand and gravel which constrains the ground water, preventing its rise to a normal water-table surface and causing artesian pressures of small magnitude.

Ground water traveling through solution channels in the underlying bedrock encounters less frictional resistance to flow than that traveling through the overlying alluvium and artesian pressures exist within the bedrock, which are of slightly greater magnitude than those within the alluvium.

These causes of ground water restraint result from the normal processes of fluvial sedimentation on a limestone terrain which is moderately dissolved in a normal manner. It is therefore probable that similar artesian phenomena, although unrecognized, may exist in the lower reaches of many large rivers. It is known that conditions responsible for the artesian effects in the lower Tennessee Valley are duplicated in the adjacent parts of the Cumberland and Ohio valleys.

## ARTESIAN WATER IN THE COASTAL AREA OF GEORGIA AND NORTHEASTERN FLORIDA.

V. T. STRINGFIELD, M. A. WARREN, AND H. H. COOPER, JR.

The area covered by this paper, comprising the six coastal counties of Georgia and two counties in northeastern Florida, is one of the most productive artesian areas in the United States. It is estimated that the artesian wells in the area yield, by artesian flow or pumping, more than 150 million gallons a day. A large part of this amount is used by six industrial plants; the remainder is used for many different industrial, public, and domestic supplies, or is discharged from flowing wells without being used.

The Ocala limestone, of Eocene age, which consists chiefly of several hundred feet of permeable limestone, is the principal water-bearing formation. The depth to the top of the formation ranges from less than 200 feet to more than 500 feet. Everywhere within about 25 to 30 miles of the coast the wells that end in the Ocala limestone will overflow at the surface, except in a few small local areas and in and near Savannah, where all wells have ceased to flow because of the large withdrawal of water.

The piezometric surface, or imaginary surface to which the artesian water will rise in tightly cased wells that penetrate the artesian formation, is at present similar to the original piezometric surface except that its coastward slope has been steepened and large cones of depression have

developed on it around Savannah and Fernandina by the large withdrawals of artesian water in those localities.

Field tests indicate that in the vicinity of Savannah the coefficient of transmissibility of the water-bearing limestone is about 250,000—that is, for each mile of width of the formation about 250,000 gallons of water a day percolates through the formation for each foot per mile of hydraulic gradient. Similar tests indicate that in the vicinity of Fernandina, Fla., the coefficient of transmissibility is somewhat less than at Savannah. The shape of the piezometric surface, together with information on the quantity of water taken from wells, indicates that in the vicinity of Brunswick, Ga., and Jacksonville, Fla., the coefficients of transmissibility are much larger than that at Savannah and Fernandina.

## *GROUND-WATER TEMPERATURE ON LONG ISLAND, N. Y., AS AFFECTED BY RECHARGE OF WARM WATER.*

M. L. BRASHEARS, JR.

(Introduced by David G. Thompson)

The water-table in an area of about forty square miles in western Long Island was below sea level in 1933. In order to prevent further overdevelopment, the New York State Water Power and Control Commission has required most of the water pumped for cooling purposes from wells constructed since then to be returned to the ground. Recharge of water having a temperature ranging from 2 to 20 degrees higher than water pumped from the ground during summer has increased from about 36,000 gallons a day in 1933 to 21,400,000 gallons a day in 1940. Ground water is considerably cooler and less expensive than surface water but this economic advantage has been greatly diminished in places because of the rise in ground-water temperature. The Federal Geological Survey has observed ground-water temperatures periodically at about 350 wells on western Long Island since 1936. Recharge of about 3,000,000 gallons a day during the summer of 1940 in an area of one-quarter square mile in Brooklyn caused temperature rises at supply wells of 0.1 to 11.1 degrees Fahrenheit. Ground-water temperatures at the end of the 1940 cooling season in this area ranged from 57.5 to 75.2 degrees as contrasted with normal temperatures of 52 to 56 degrees in areas not especially affected by recharge. Appreciable rise of temperature has been observed only at areas where considerable recharge occurs. However, the continued recharge of increasing quantities of warm water probably will cause a gradual long time rise of temperature to some equilibrium point above the present yearly average in unaffected areas.

## *PROBLEMS PRESENTED BY DEEP SOLUTION CAVITIES IN DAM CONSTRUCTION.*

BERLEN C. MONEYMAKER AND PORTLAND P. FOX.

In dam sites on limestone and related carbonate rocks, solution cavities are almost invariably present in foundations and abutments. The size and character of the cavities and the depth to which they occur are dependent upon the geomorphic history of the region and the local geologic

structure. In some areas, solution cavities are present to depths as great as 225 feet below the river bed. In the construction of dams, especially large dams, solution cavities present numerous problems among which bearing strength and water tightness are paramount. Although few dam sites are so bad that it is impossible to construct safe and successful dams upon them, the cost of the necessary remedial treatment may be prohibitive. Cavities sufficiently large and near the surface to render the foundation incapable of bearing the stresses to be imparted by the dam may, in many cases, be eliminated at little extra cost by excavation. Deep cavities, if not too numerous, may be effectively and economically sealed by a systematic drilling and grouting program.

## *THE PLACE OF OBSERVATIONAL GEOLOGY: PAST AND PRESENT.*

BENJAMIN L. MILLER.

Of the major natural sciences, Geology is the most composite one of all. Most geological researches draw upon one or more of the other sciences and some recent advances have been in the border lands of several of the basic sciences. Geologists first drew upon biology and chemistry with occasional incursions into physics. In fact when the use of some physical methods were first proposed, they were regarded in some quarters as only new adaptations of the divining rod and other similar quacks.

Sir Archibald Geikie says that William Smith, the Father of English Geology, was concerned wholly in the "observation of facts." As he traveled about England he was continually studying the outcrops and recording his observations. His method was so generally followed that one may designate the beginnings of geological research as the period of "observational geology." This method still remains fundamental in most geologic work but is now happily supplemented by other methods and tools. The field of geology is now so broad that no person can compass the whole. In certain lines the observational method still remains the sole guide and in practically all is eminently essential so that the main emphasis in the training of students should still be placed on the long-established and successful method.

## *RESULTS TO DATE OF EXPLORATION FOR GROUND WATER IN THE BURIED GENESEE VALLEY.*

J. EDWARD HOFFMEISTER.

(Introduced by Quentin D. Singewald.)

A large pre-glacial valley, the course of which corresponds roughly with that of the present Genesee River, was described some years ago by Professor Herman L. Fairchild, who called it the Irondogenesee valley. It has been considered a potential source of a large amount of ground water.

This paper describes the course of the valley and the ground water locations already developed. More recent developments are also described. The City of Rochester, in order to supplement its water supply, has begun a study of the possibilities of the valley. A seismic survey to determine the exact location of the buried valley at a strategic point, near the village of

Rush, has been made by the Geophysical branch of the U. S. Geological Survey cooperating with the City. Two north-south traverses revealed the existence of a broad, deep, east-west valley about one mile north of its supposed location. It has been recommended to the City that a similar survey be made at another strategic place some miles farther downstream before test drilling is begun.

## *SIGNIFICANT DEVELOPMENTS IN QUEBEC'S MINERAL INDUSTRY.*

G. M. SCHWARTZ.

Quebec has long been an important producer of minerals, but metals played only a minor role until 1927, when the Horne Mine, at Noranda, was opened and metal production and exploration became very active.

The total mineral production in 1939 was valued at $77,125,985, an increase of 12 per cent over 1938, and three times the 1926 production. Metals were valued at $1,897,528 in 1926 and $47,813,493 in 1939. Gold and copper form the bulk of the production, but zinc is also important and several lesser metals contribute smaller amounts. The great importance of asbestos deposits in the Province is well known; its production in 1939 was valued at $15,858,492.

The astronomic rise in mineral production has caused a greatly increased interest in the mineral industry by the people and government. The staff of the Bureau of Mines, which also supervises geological work, has been greatly increased and the provincial government has aided the French-speaking Laval University in establishing a School of Mines and Geology. A school has also been established at Val d'Or, in Western Quebec, to train workmen in drilling, blasting, and other phases of mining work.

The new building at Laval University for the study of geology, mineralogy, mining and metallurgy is most modern, and is very well equipped and staffed.

## *THE GEOLOGY AND ORE DEPOSITS OF SOUTHWESTERN SARDINIA.*

CHAS. H. BEHRE, JR.

Southwestern Sardinia, Italy's leading ore district, yields about 65 per cent of Italian lead and 1.5 per cent world lead. In zinc it is the eighth ranking district, furnishing 85 per cent of Italian and 4 per cent of the world. Fault troughs bound the deposits east and south; the ocean north and west. They occur in Cambrian to Silurian limestones, covered locally by Mesozoic and Tertiary sediments and lavas. Detailed structure is not wholly understood. The region is rugged; the water table deep.

There are two groups of deposits. The larger, near Iglesias, are mainly replacements in limestones, with associated dolomitization and silicification, and commonly barite. Mineralization is localized by fissures, bedding plane partings in folds, selectively replaced strata, and especially, intense shattering with development of stockworks like Monteponi, 150 meters across and 300 meters deep. The ores are largely oxidized zinc, locally rich in lead and silver. Near Arbus are veins richer in lead that radiate from a Carboniferous granite cupola, presumably connected underground with buried masses at Iglesias. Nearby are small nickel and arsenic veins. Mineralization at Iglesias was more intense than at Arbus because of more calcareous rocks and greater shattering, thus complicating a zoned pattern.

# SCIENTIFIC NOTES AND NEWS

L. H. HART of the geological staff of Anaconda Copper Mining Co., Butte, Montana, has accepted a position with U. S. Smelting and Refining Co. with headquarters in Salt Lake City.

FRANK AYER, general manager of Roan Antelope Copper and Mufulira Copper Companies in Northern Rhodesia, is now consulting engineer in New York for both organizations.

DAVID GALLAGHER has joined the U. S. Geological Survey and is now engaged in strategic mineral work in the Southern states.

G. W. RODDEWIG has returned to Beverly Hills, California after three years as general manager for the Compañia Minera Unificada del Cerro de Potosi, at Potosi, Bolivia.

T. S. LOVERING will be stationed near Tucson, Arizona by the U. S. Geological Survey until after the middle of February.

The REKTOR of the BERGAKADEMIE OF FREIBERG announces that the celebration of the 175th anniversary of the institution has been indefinitely postponed.

A. P. BEAVAN, formerly geologist for O'Brien Gold Mines, Ltd., is in charge of exploration for Northland Mines, Ltd. in the East Kirkland Lake District, Ontario.

THOMAS P. THAYER, assistant geologist of the U. S. Geological Survey, is investigating Cuban deposits of manganese and chrome.

A NATIONAL RESEARCH DEFENSE COMMITTEE is investigating beryllium in various phases of national defense. Any information regarding deposits of beryl, particularly deposits of lower grade material susceptible to concentration, would be welcomed. Please communicate with Alan M. Bateman, Yale Station, New Haven, Conn.

A. J. MARTIN of the Denver office of the mineral production and economics division of the U. S. Bureau of Mines has been placed in charge of the Joplin office of the Bureau.

JOHN MCCARTHY has resigned as geologist of the Central Patricia Gold Mines, Ltd., Ontario to accept a position as geologist with the Fresnillo Co., Mexico. His place at Central Patricia is being taken by ASHTON JOHNSTON.

The U. S. GEOLOGICAL SURVEY is sending several of its geologists to different South American countries to investigate there resources of strategic minerals that might, if necessary, be drawn upon for use in the United States.

S. H. CATHCART has just returned to the United States, after a long delayed trip around the Cape of Good Hope, from the Mesopotamian oil fields.

EARL IRVING, geologist for the E. P. Haliburton Co. of Los Angeles, has returned to their silver properties in Honduras.